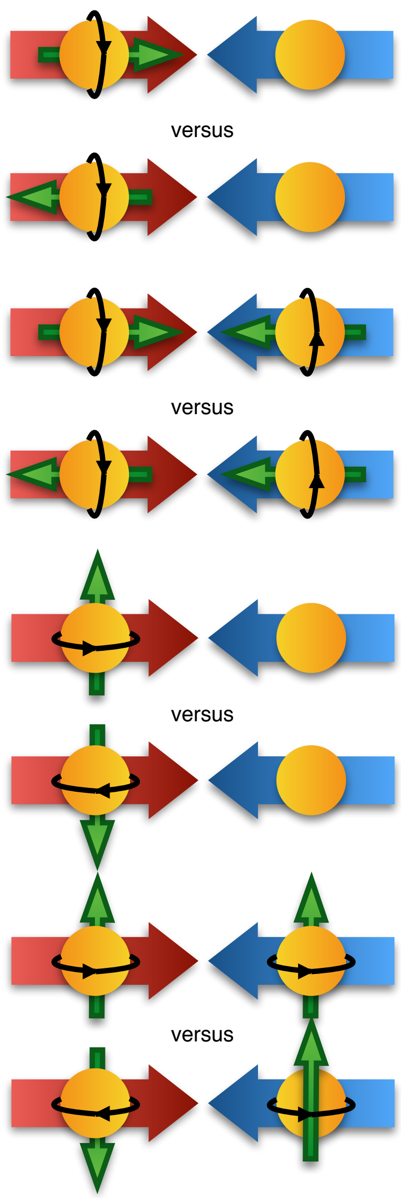
Spin Physics and EIC

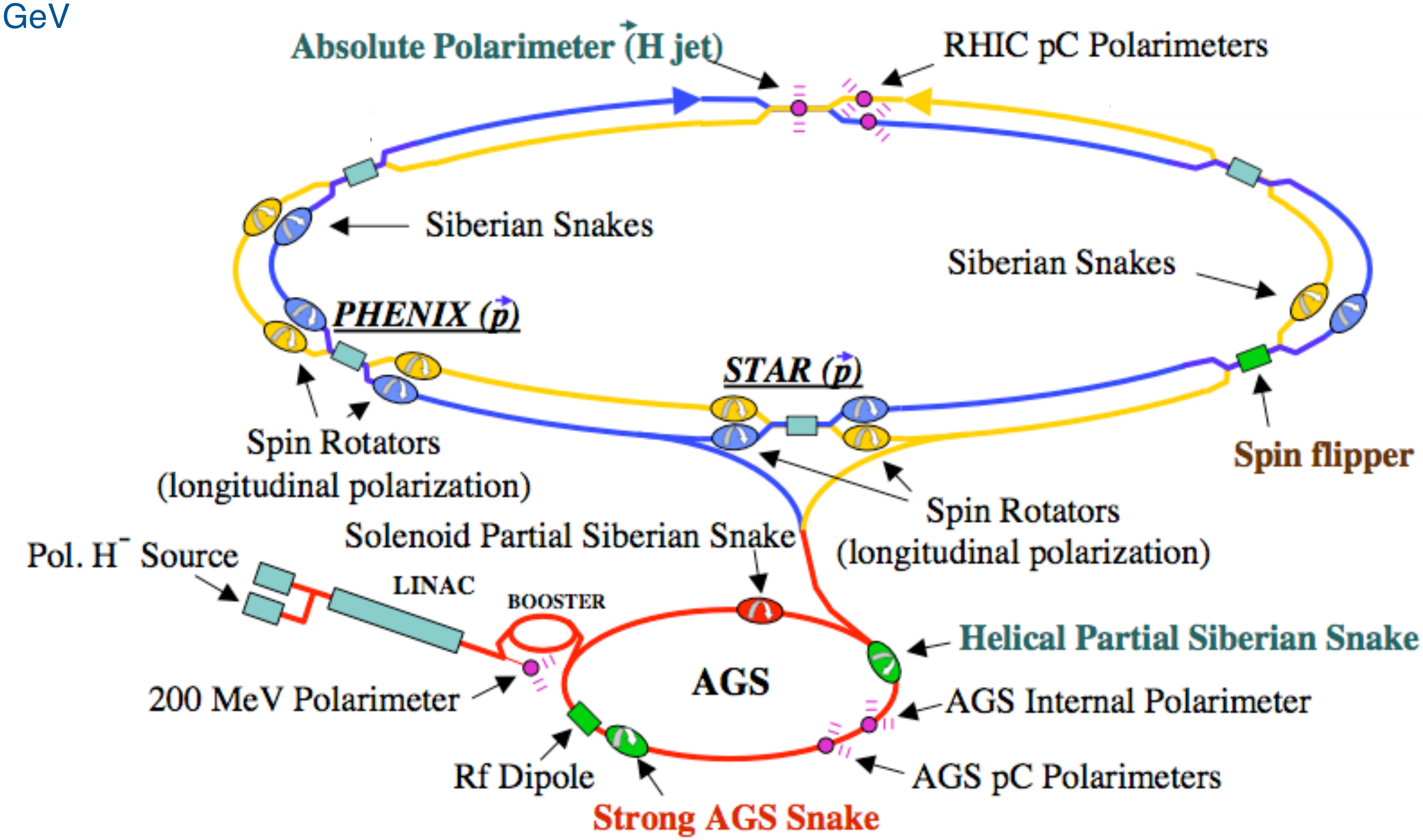
- RHIC Spin Program
- EIC
- Bridging the Gap

RHIC - Polarized Proton-Proton Collider

Unique opportunities to study nucleon spin properties and spin in QCD:

$\sqrt{s}$ = 62, 200, and 500 GeV



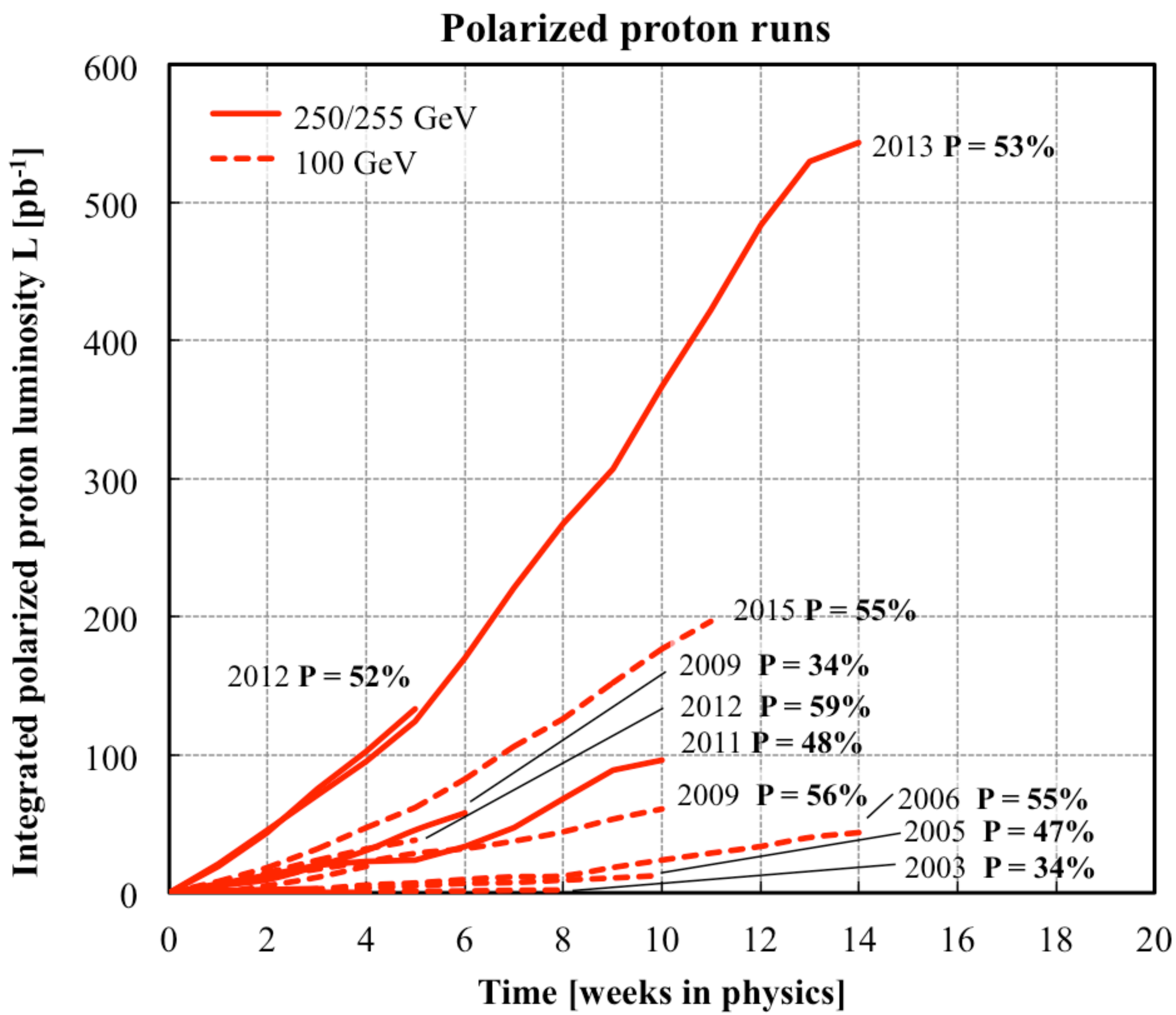


Key technical involvement: real-time measurement of luminosity and polarization direction with segmented BBC and ZDC(-SMD), and fast memory-mapped scaler systems (2004-present; most recently with former postdoc Andrew Manion).

RHIC - Polarized Proton-Proton Collider

Unique opportunities to study nucleon spin properties and spin in QCD:

Longitudinal data	**STAR**
√s = **200 GeV**	
2005	
2006	35 pb^{-1}
2009	
2015	50 pb^{-1}
√s = **500 GeV**	
2009	
2011	
2012	400 pb^{-1}
2013	
Transverse data	
√s = **200 GeV**	
2006	
2008	38 pb^{-1}
2012	
2015	40 pb^{-1}
√s = **500 GeV**	
2011	25 pb^{-1}
(2017)	(400 pb^{-1})

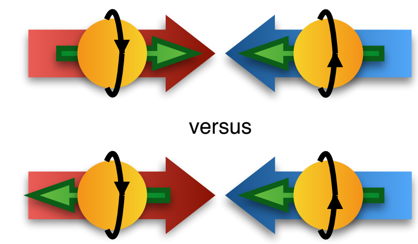


50-60% polarization

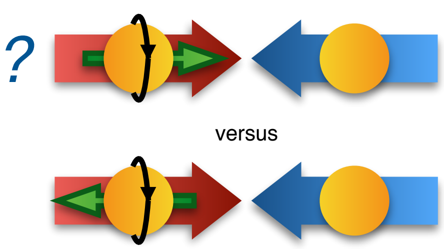
Main analysis focus: gluon and (anti-)quark polarizations, *initial* and *precise* data

The RHIC Spin Physics Program - Key Questions

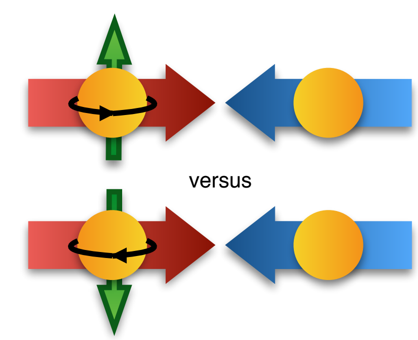
- *What is the polarization of gluons in the polarized proton (HP12)?*



- *What is the polarization of the light quarks and anti-quarks (HP8)?*

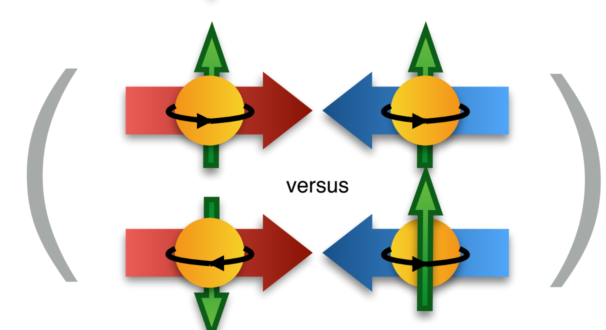


- *Does the Sivers' function change sign in proton-collisions compared to DIS (HP13)?*

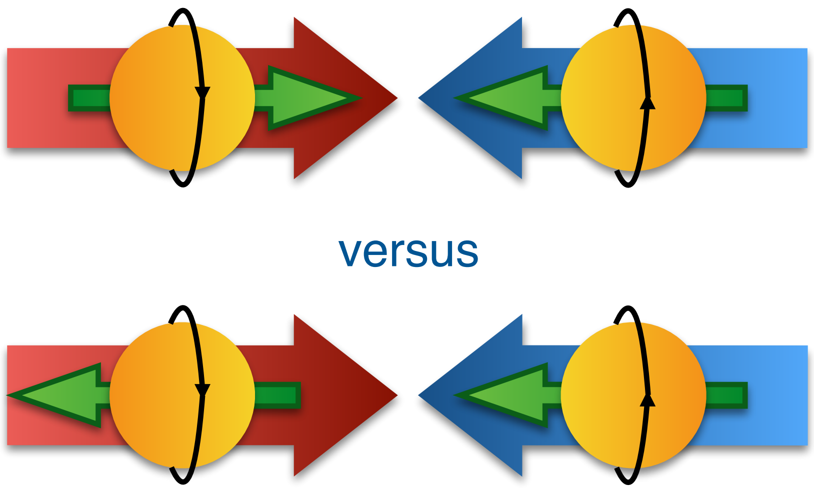


- *What are the quark transversity distributions?*

- *What is the origin of large forward A_N?*



Gluon Polarization



Gluon Polarization at RHIC - Asymmetry A_{LL}

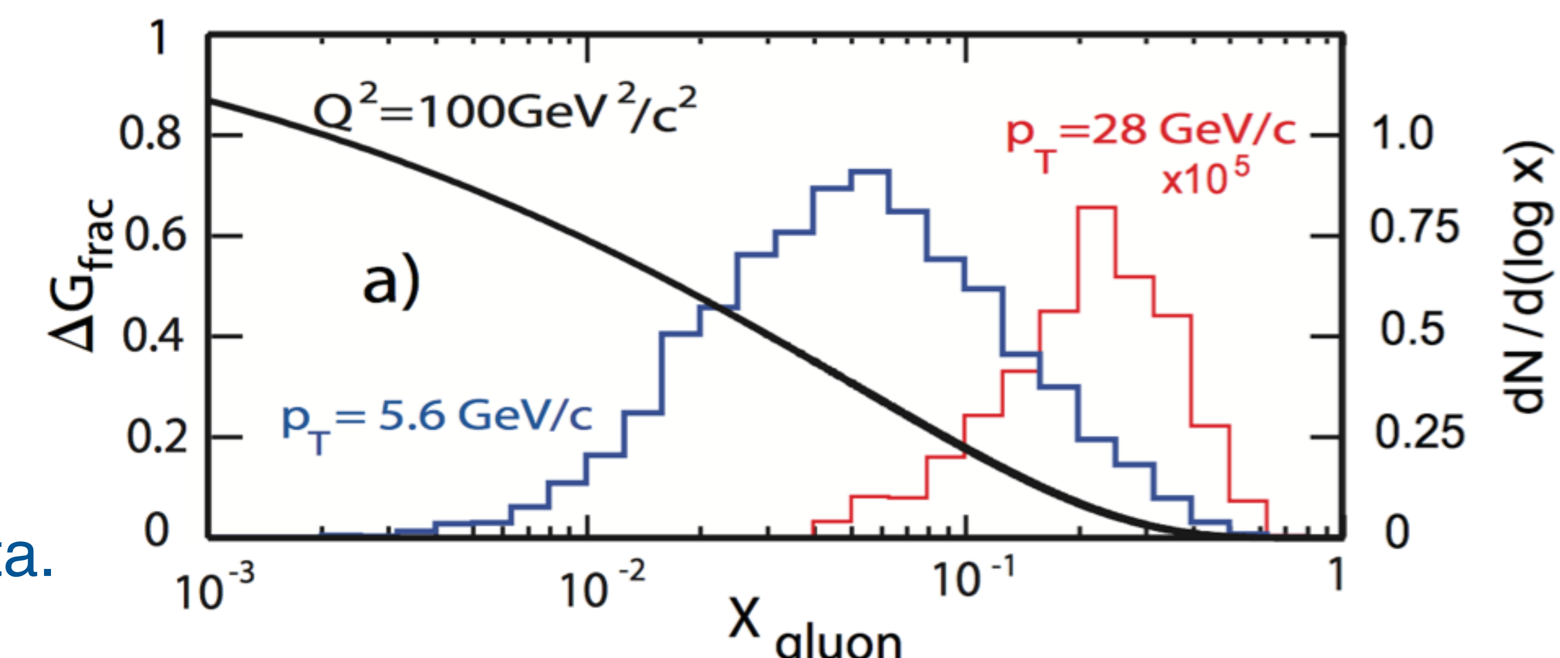
Measurement: $$A_{LL} = \frac{\sigma^{\uparrow\uparrow} - \sigma^{\uparrow\downarrow}}{\sigma^{\uparrow\uparrow} + \sigma^{\uparrow\downarrow}} \stackrel{?}{=} \sum_{f=q,g} \frac{\Delta f_1}{f_1} \otimes \frac{\Delta f_2}{f_2} \otimes \hat{a}_{LL} \otimes (\text{fragmentation functions})$$

- Detect and reconstruct jet,
- Extract beam-spin dependent yields,
- Measure relative luminosity for different spin configurations, beam polarization
- Evaluate double beam-helicity asymmetry A_{LL}

Inclusive jets at central rapidities: well understood and abundantly produced, sizable partonic asymmetries, contributions from several sub-processes; qg being the largest above ~10 GeV at RHIC, probe a wide range in gluon momenta, x_{gluon}, for each p_T:

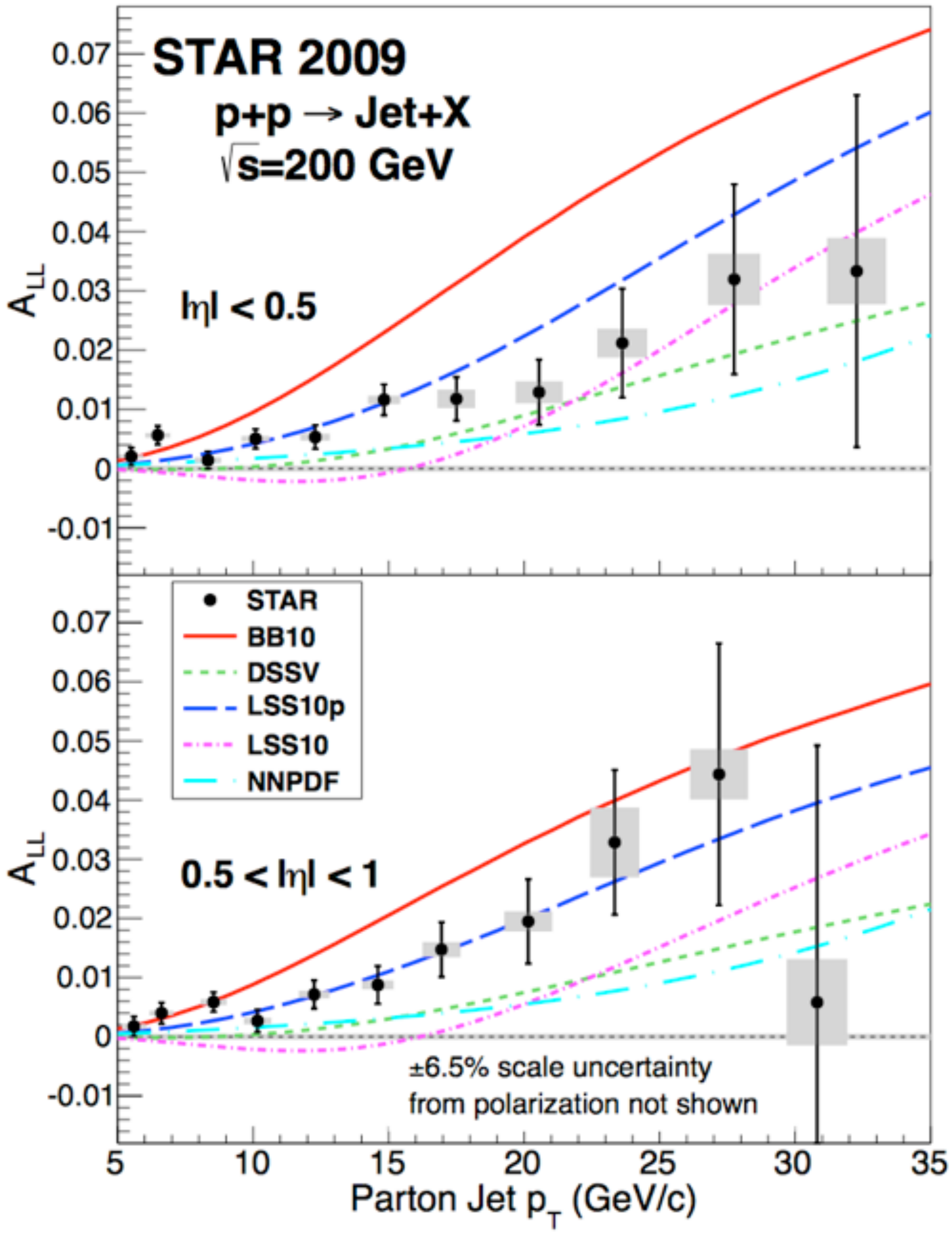
Key roles in:

- *initial* STAR paper on fully reconstructed jets and the double beam helicity asymmetry in their production:
  Phys.Rev.Lett. 97 (2006), 252001, 205 cit.
- increasingly *precise* follow-up data.



Gluon Polarization - *Precision* A_{LL} from STAR

Phys.Rev.Lett 115 (2015) 092002, 52 citations



Significant advance compared to first RHIC-spin data (2003, 2004):

- about an order in precision,
- two to three times the kinematic range compared with initial RHIC-spin data,

A_{LL} is positive for large p_T, indicative of *positive gluon polarization,*

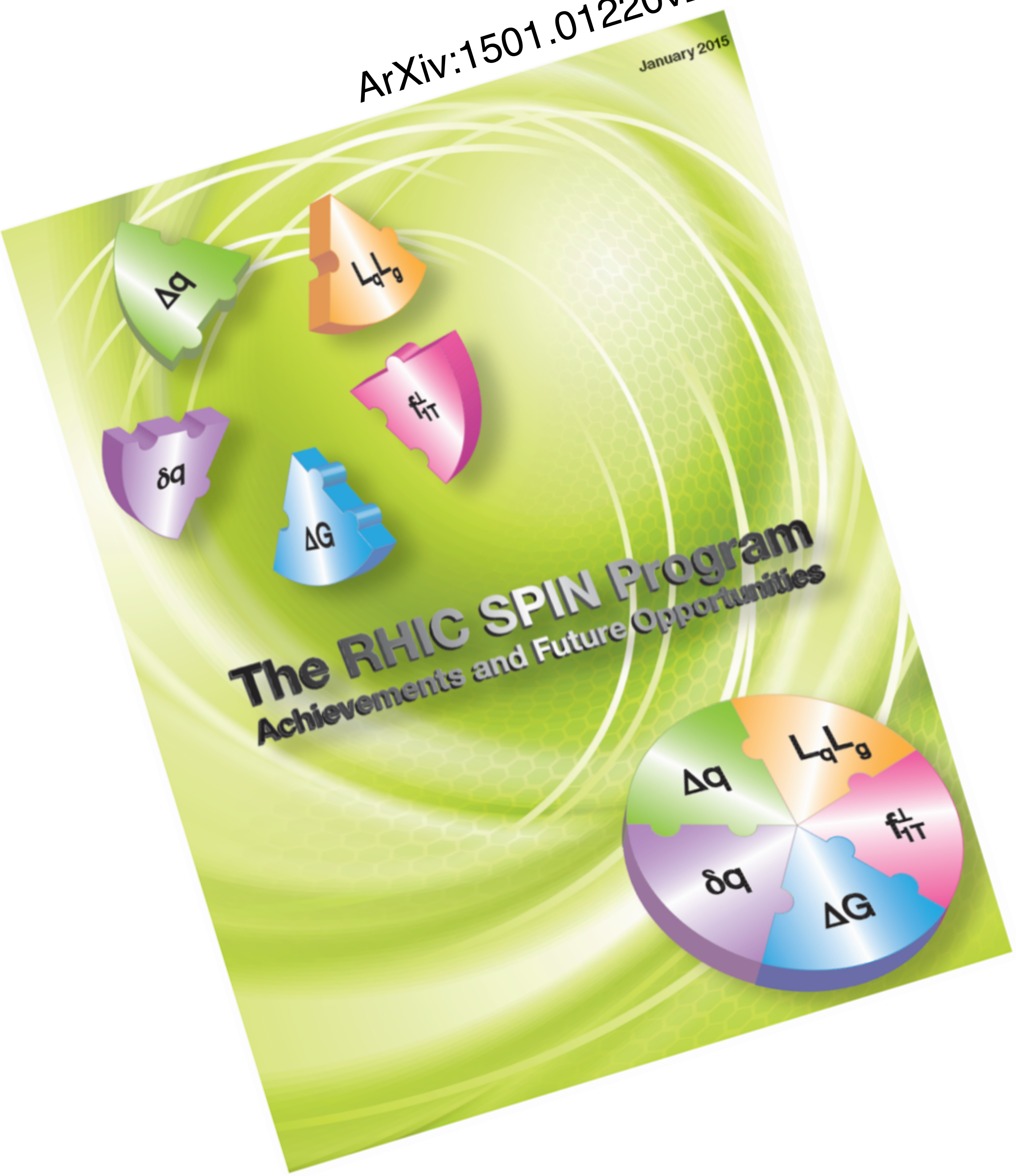
"a significant breakthrough" - 2015 LRP

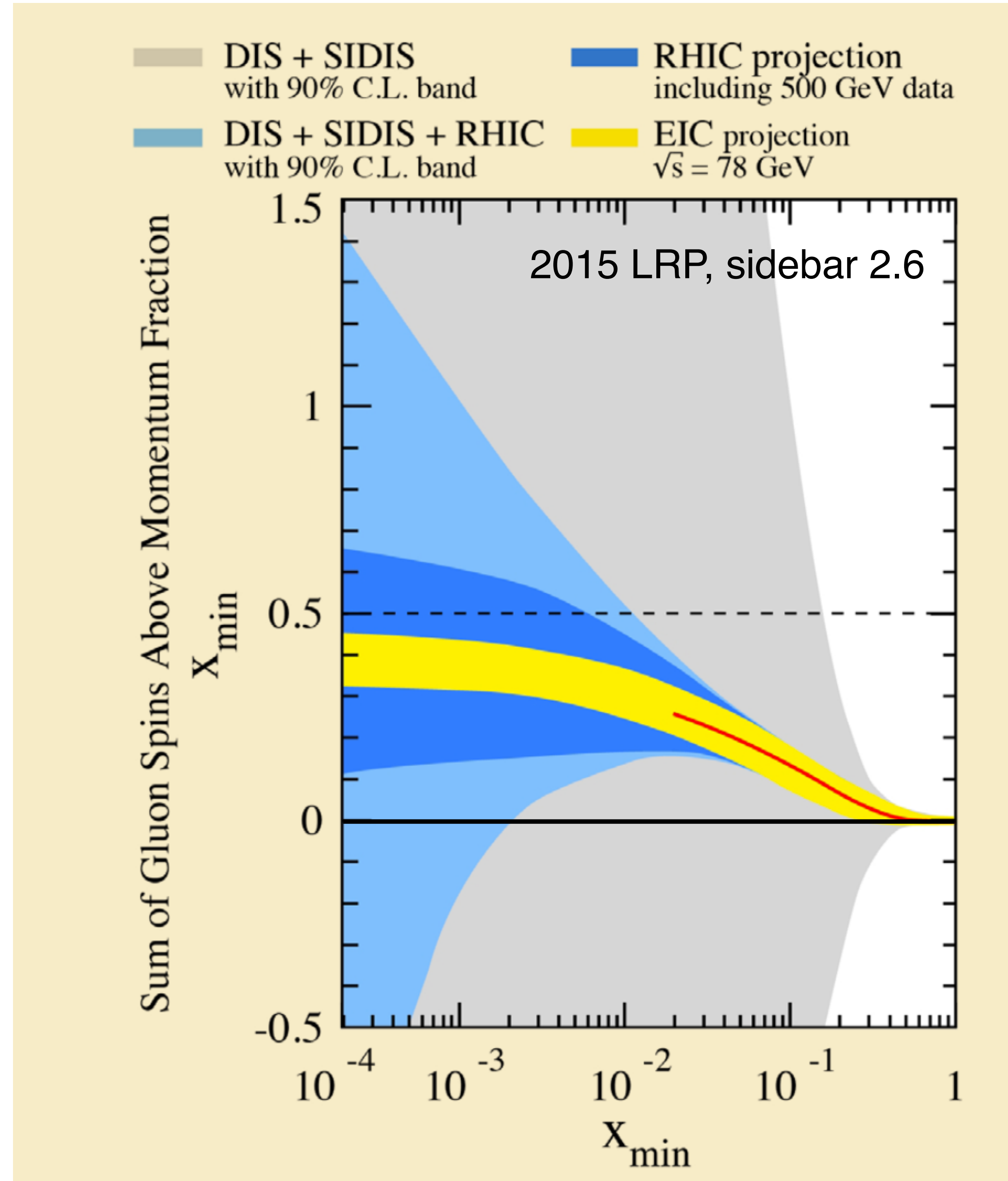
Initial sensitivity to different gluon fractional momenta, x_g, from rapidity dependence,

Key roles in publication.

Gluon Polarization - Status and what is next?

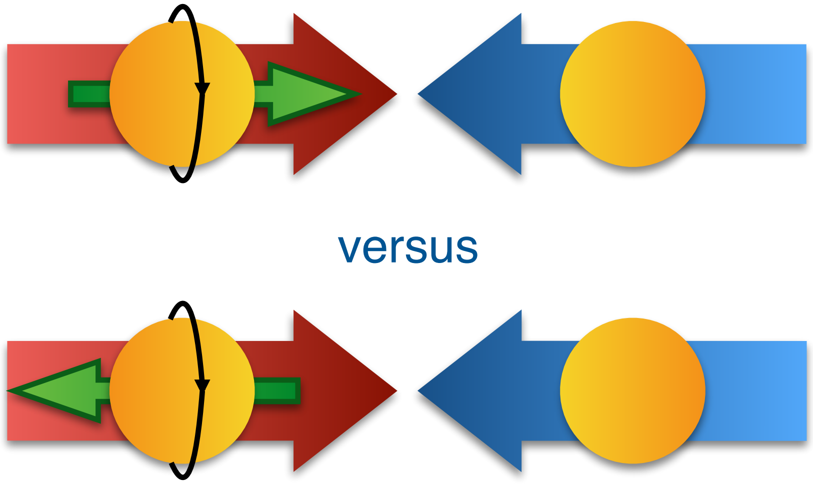
ArXiv:1501.01220v2



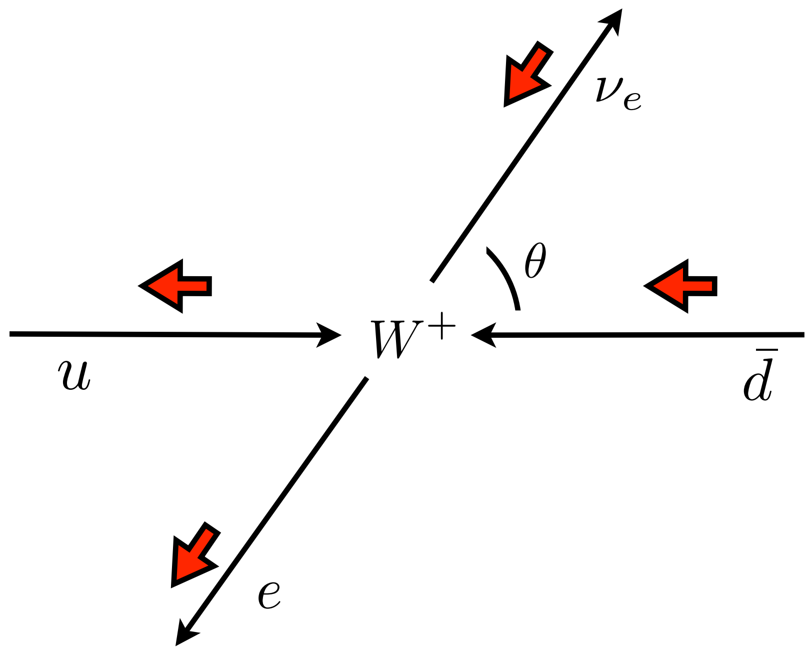


Our next steps: analysis of 2015 jet data,
a forward upgrade, *if realized*, to extend data to smaller x_{gluon}
Electron-Ion-Collider (EIC)

Quark Polarization



Quark Polarization at RHIC - Asymmetry A_L



√s = 500 GeV above W production threshold,

Experiment Signature:

large p_T lepton, missing E_T

Experiment Challenges:

charge-ID at larger Irapidityl
electron/hadron discrimination
luminosity hungry!

$$\Delta\sigma^{\mathrm{Born}}(\vec{p}p \to W^+ \to e^+\nu_e) \propto -\Delta u(x_a)\bar{d}(x_b)(1+\cos\theta)^2 + \Delta\bar{d}(x_a)u(x_b)(1-\cos\theta)^2$$

Spin Measurements:

$$A_L(W^+) = \frac{-\Delta u(x_a)\bar{d}(x_b) + \Delta\bar{d}(x_a)u(x_b)}{u(x_a)\bar{d}(x_b) + \bar{d}(x_a)u(x_b)} = \begin{cases} -\dfrac{\Delta u(x_a)}{u(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{d}(x_a)}{\bar{d}(x_a)}, & x_b \to 1 \end{cases}$$

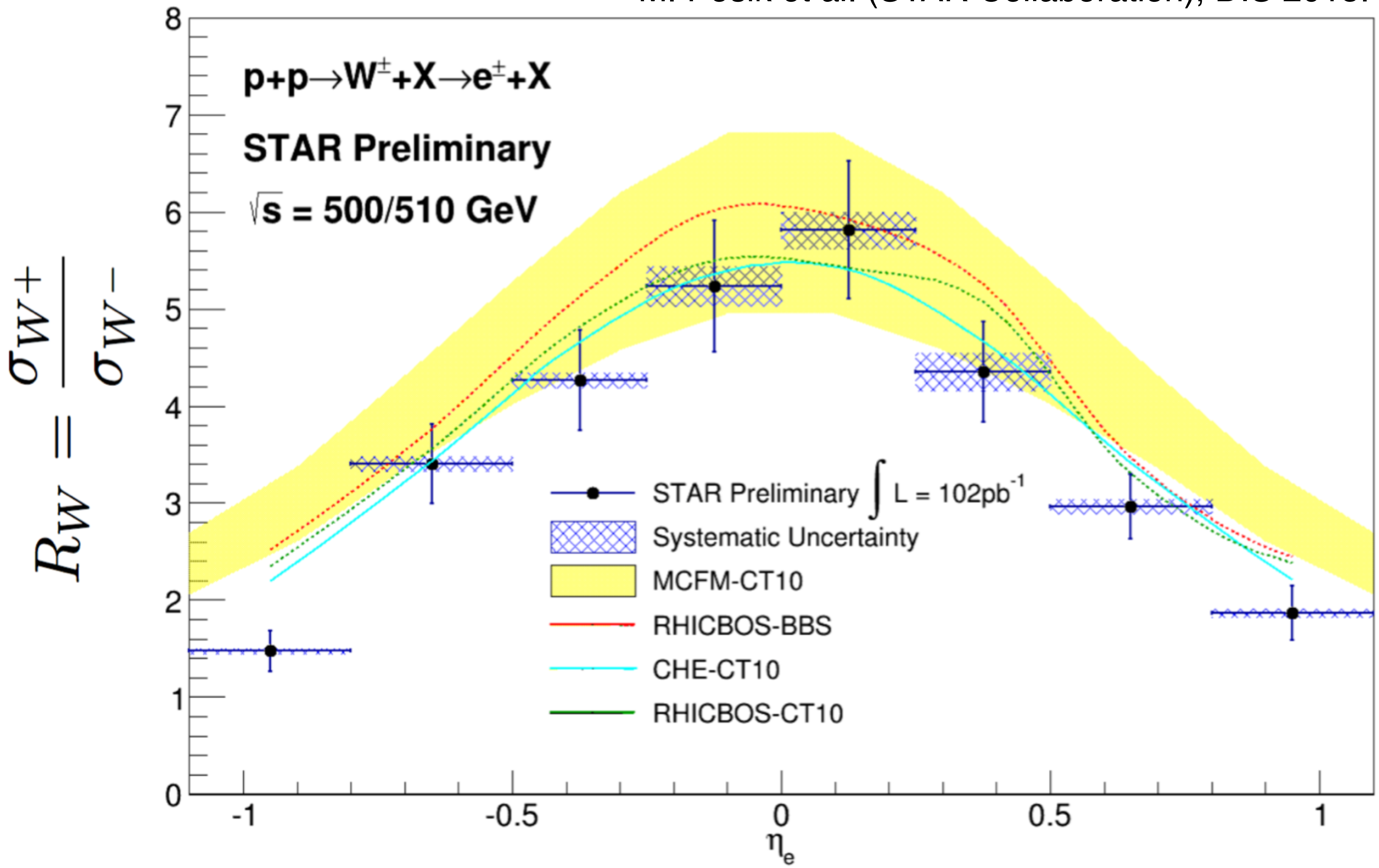
$$A_L(W^-) = \begin{cases} -\dfrac{\Delta d(x_a)}{d(x_a)}, & x_a \to 1 \\ \dfrac{\Delta\bar{u}(x_a)}{\bar{u}(x_a)}, & x_b \to 1 \end{cases}$$

Analysis tour-de-force for both experiments!

- *Development of 500 GeV real-time polarimetry,*
- *Analysis of precision data.*

Intermezzo - Cross Section Ratio

M. Posik et al. (STAR Collaboration), DIS 2015.

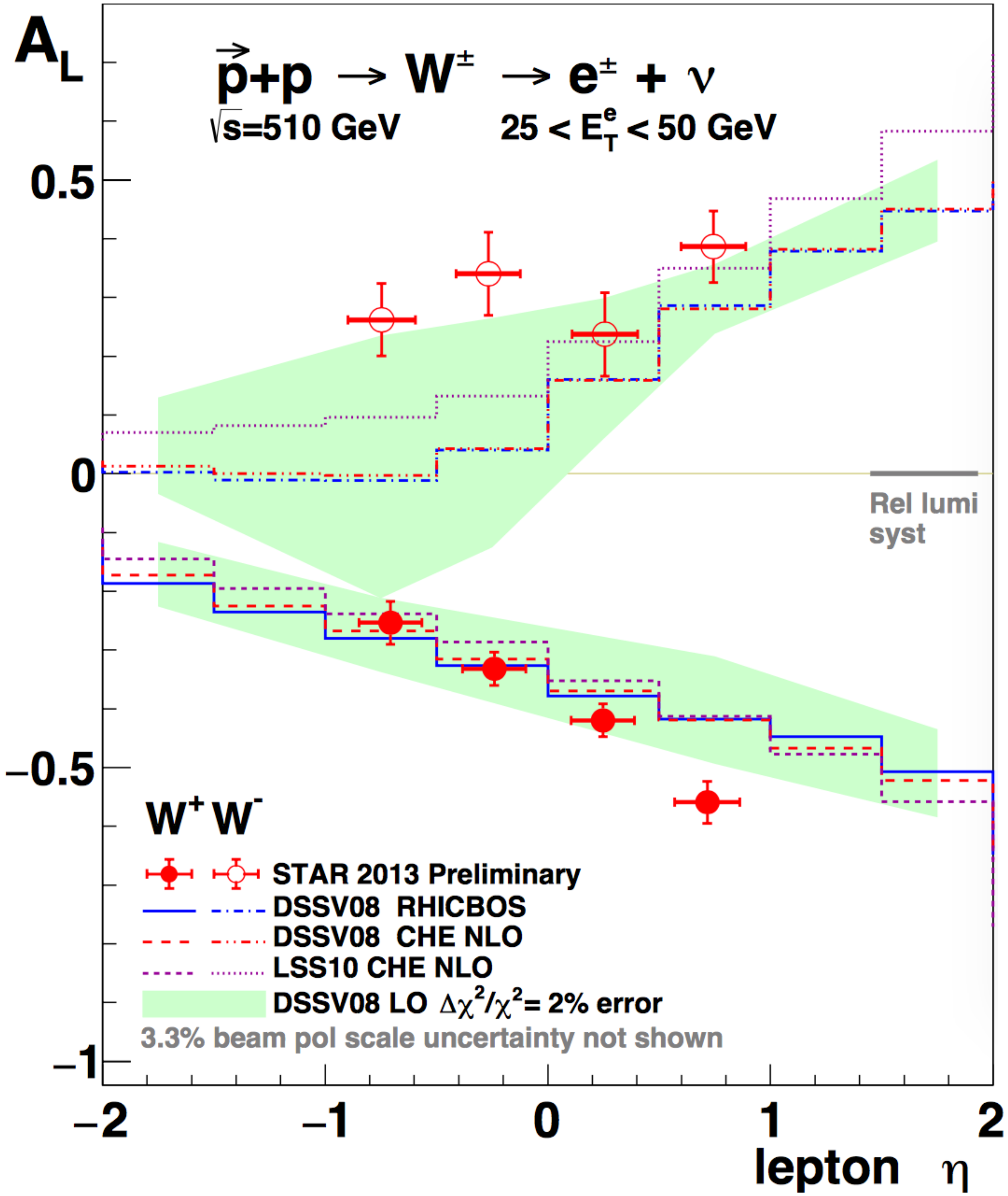


Preliminary data from 102 pb^{-1} obtained during run-11 and run-12,
~300 pb^{-1} recorded during run-13,
~400 pb^{-1} anticipated from run-17,

Complementary to NA51, E866, and SeaQuest; STAR data cover ~0.1 < x < ~0.3

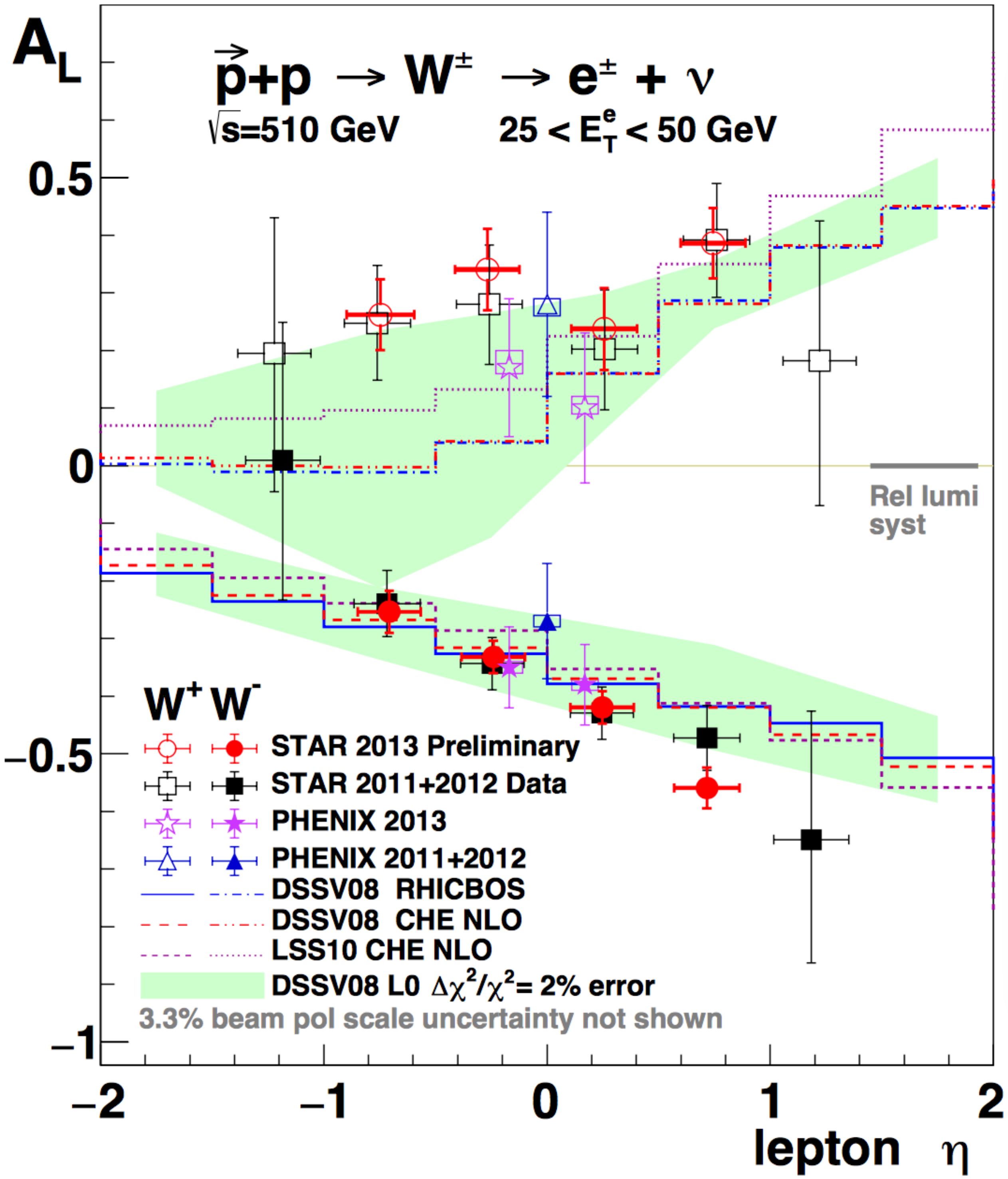
A potential analysis opportunity (longer-term, run-17 data)

Quark Polarizations - *Precision* A_L from STAR



Released by postdoc Jinlong Zhang, for the collaboration, at INPC-2016

Quark Polarizations - *Precision* A_L from STAR



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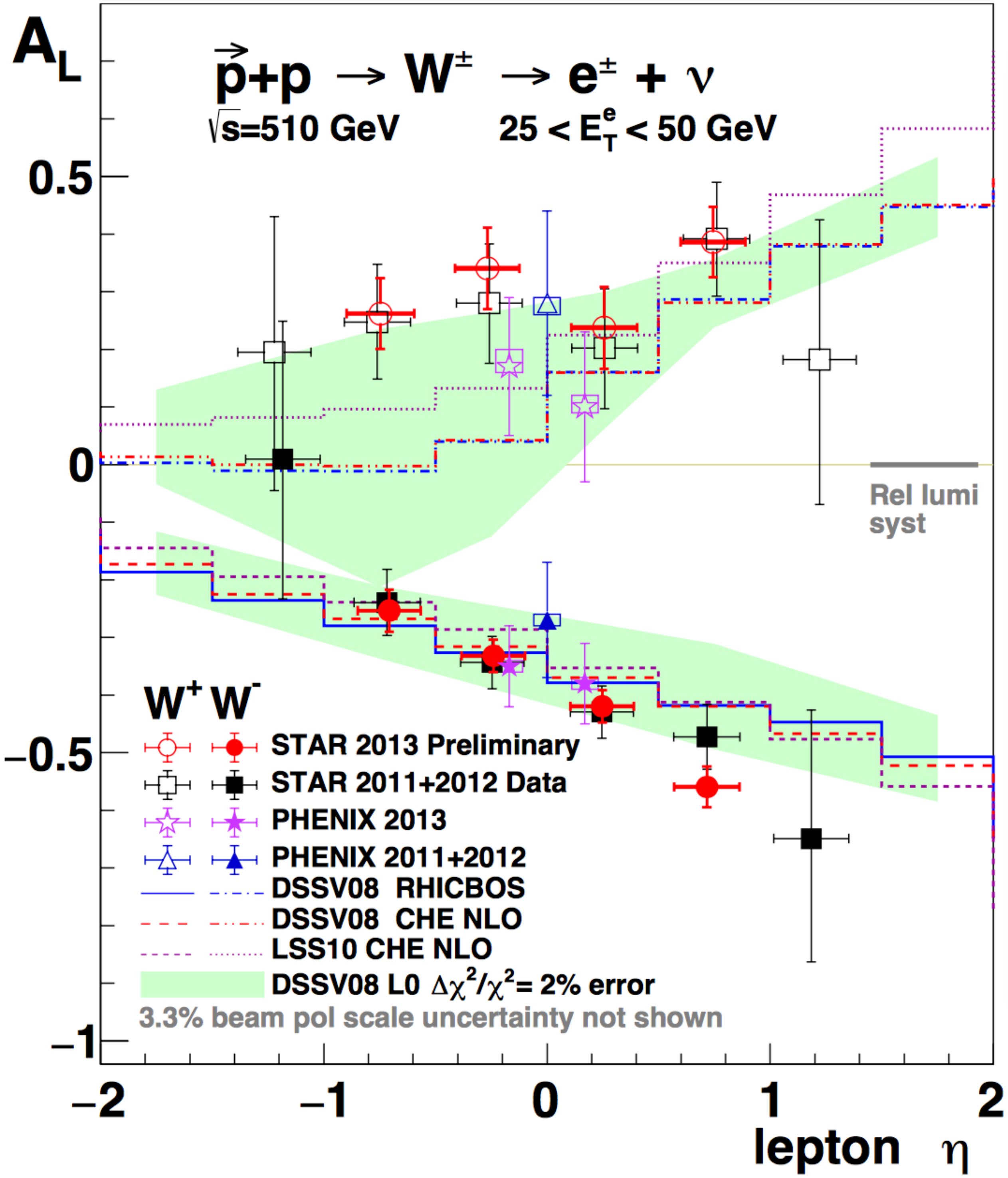
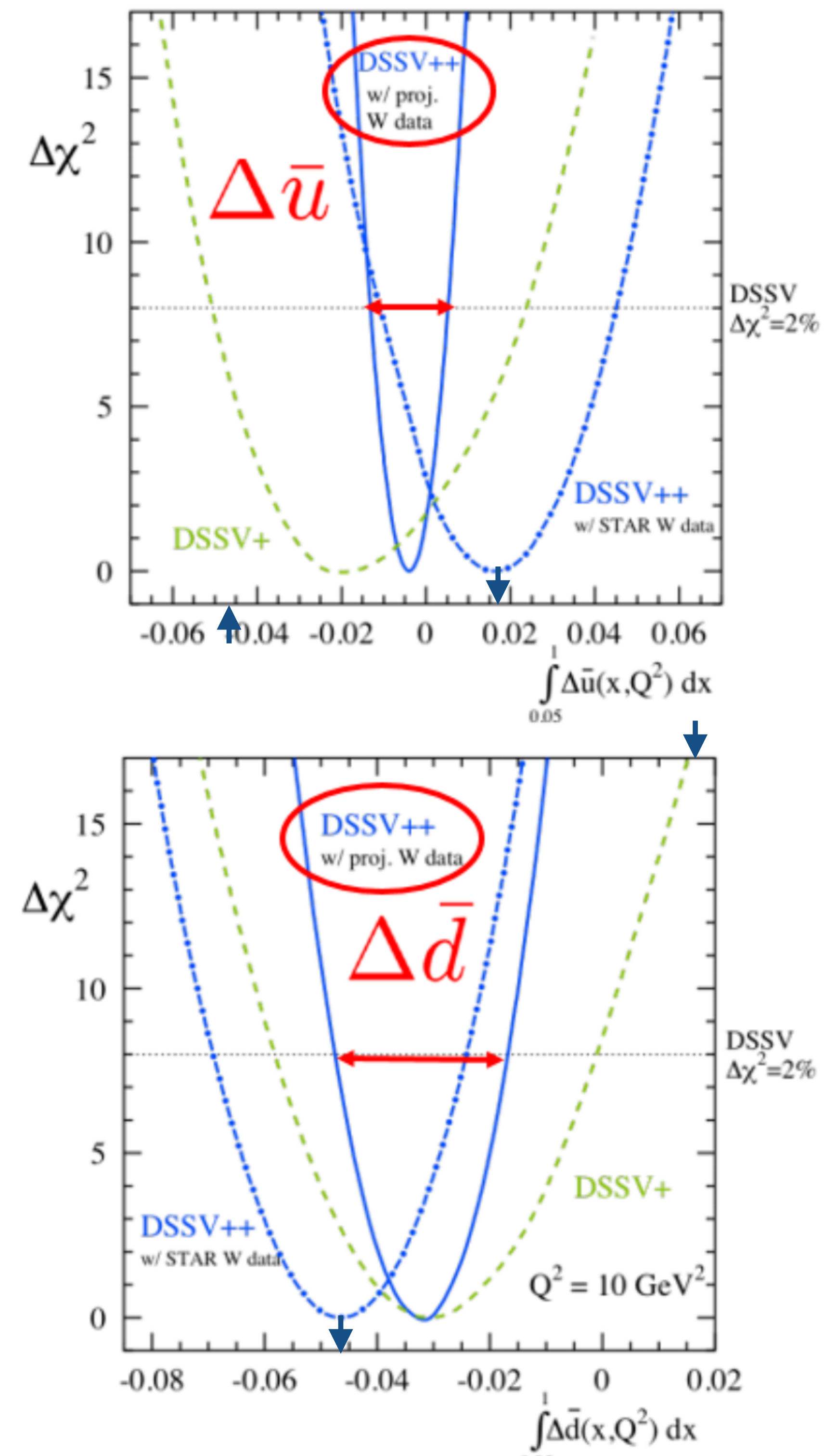
Quark Polarizations - *Precision* A_L from STAR

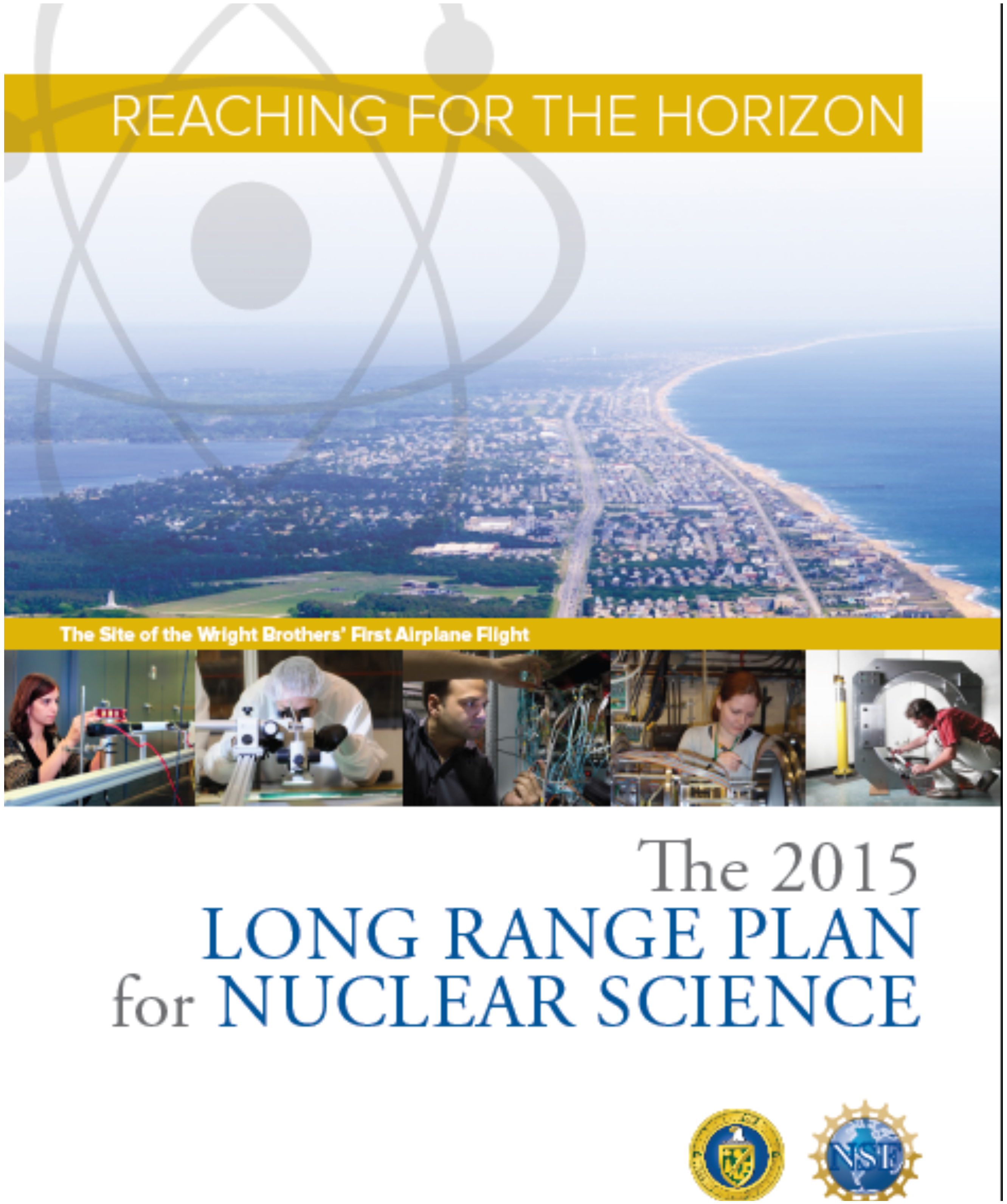




Our next steps: extend coverage,
finalize and publish.

$$\Delta\bar{u} > \Delta\bar{d}, \text{ while } \bar{d} > \bar{u}$$

Electron Ion Collider



Recommendation III

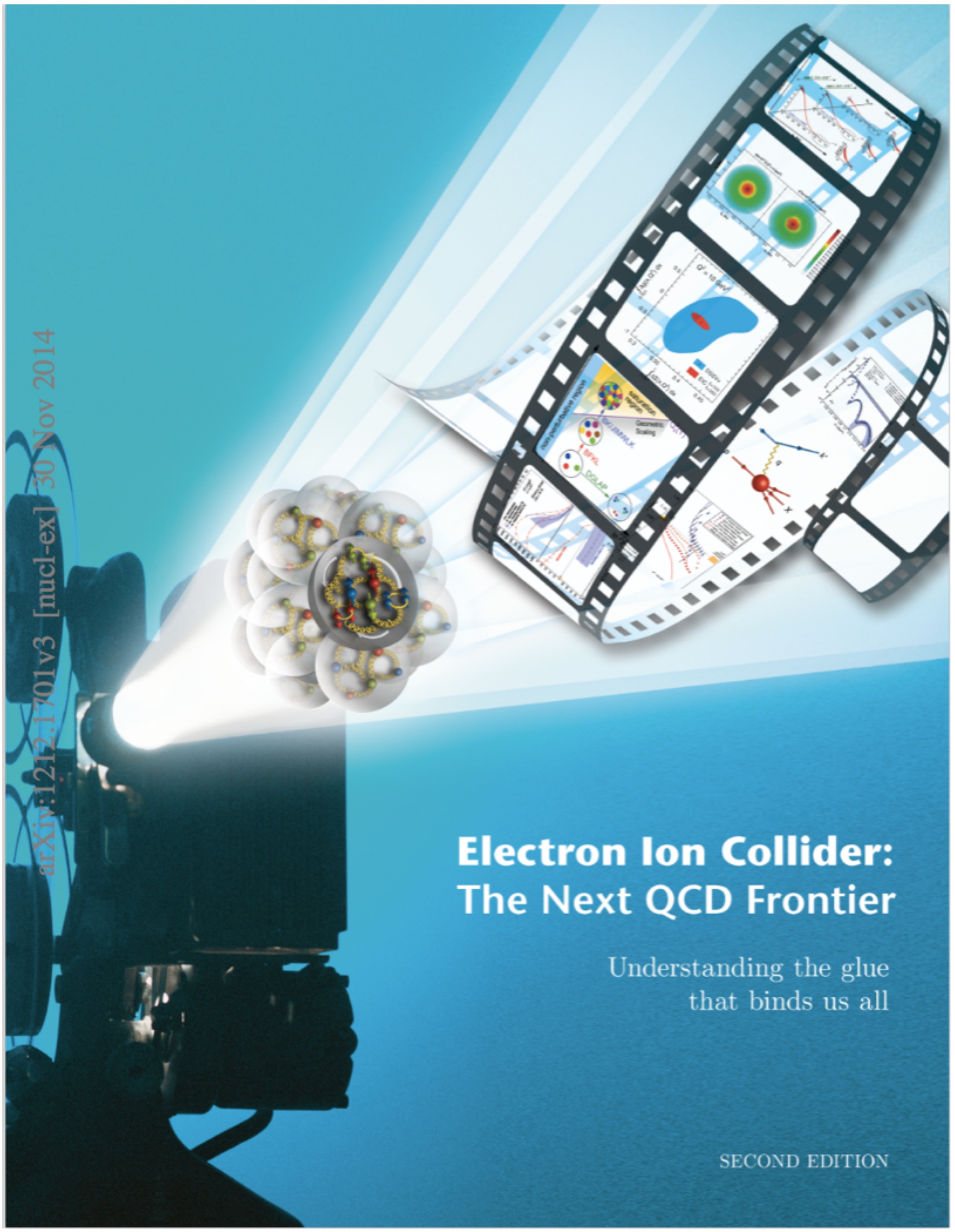
Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

The EIC will, for the first time, precisely image gluons in nucleons and nuclei. It will definitively reveal the origin of the nucleon spin and will explore a new quantum chromodynamics (QCD) frontier of ultra-dense gluon fields, with the potential to discover a new form of gluon matter predicted to be common to all nuclei.

This science will be made possible by the EIC's unique capabilities for collisions of polarized electrons with polarized protons, polarized light ions, and heavy nuclei at high luminosity.

U.S. Based Electron Ion Collider



Eur. Phys. J. A52 (2016) no.9, 268 - 284 citations

Overall Editors:
A. Deshpande (Stony Brook), Z-E. Meziani (Temple), J. Qiu (BNL)

Gluon Saturation in e+A:
T. Ullrich (BNL) and Y. Kovchegov (Ohio State)

Nucleon spin structure (inclusive e+N):
E. Sichtermann (LBNL) and W. Vogelsang (Tubingen)

GPD's and exclusive reactions:
M. Diehl (DESY) and F. Sabatie (Saclay)

TMD's and hadronization and SIDIS:
H. Gao (Duke) and **F. Yuan (LBNL)**

Parton Propagation in Nuclear Medium:
W. Brooks (TSFM) and J. Qiu(BNL)

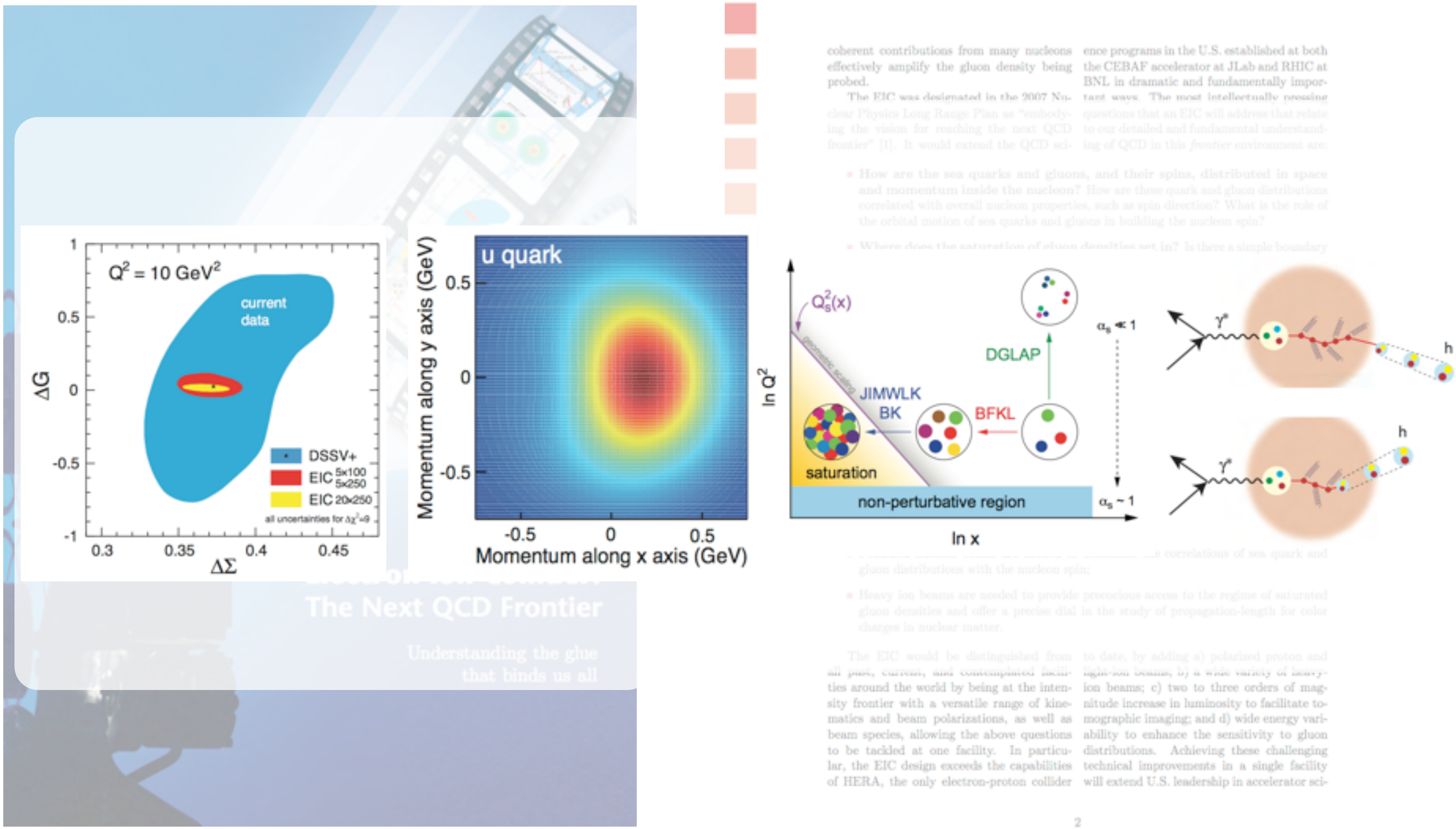
Electroweak physics:
K. Kumar (U Mass) and M. Ramsey-Musolf (Wisconsin)

Accelerator design and challenges:
A. Hutton (JLab) and T. Roser (BNL)

Detector design and challenges:
E. Aschenauer (BNL) and T. Horn (CUA)

Senior Advisors:
A. Mueller (Columbia) and R. Holt (ANL)

U.S. Based Electron Ion Collider



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U.S. Based Electron Ion Collider

Key questions:

- *How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleus?*
- *Where does the saturation of gluon densities set in?*
- *How does the nuclear environment affect the distribution of quarks and gluons and their interactions in nuclei?*

Key measurements:

- *Inclusive Deep-Inelastic Scattering,*
- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
- *Exclusive deep-inelastic scattering,*
- *Diffraction.*

Eur. Phys. J. A52 (2016) no.9, 268 - 284 citations

U.S. Based Electron Ion Collider

Key requirements:

- *Electron identification - scattered lepton*
- *Momentum and angular resolution - x, Q^2*
- *π^+, π^-, K^+, K^-, p^+, p^-, ... identification, acceptance*
- *Rapidity coverage, t-resolution*

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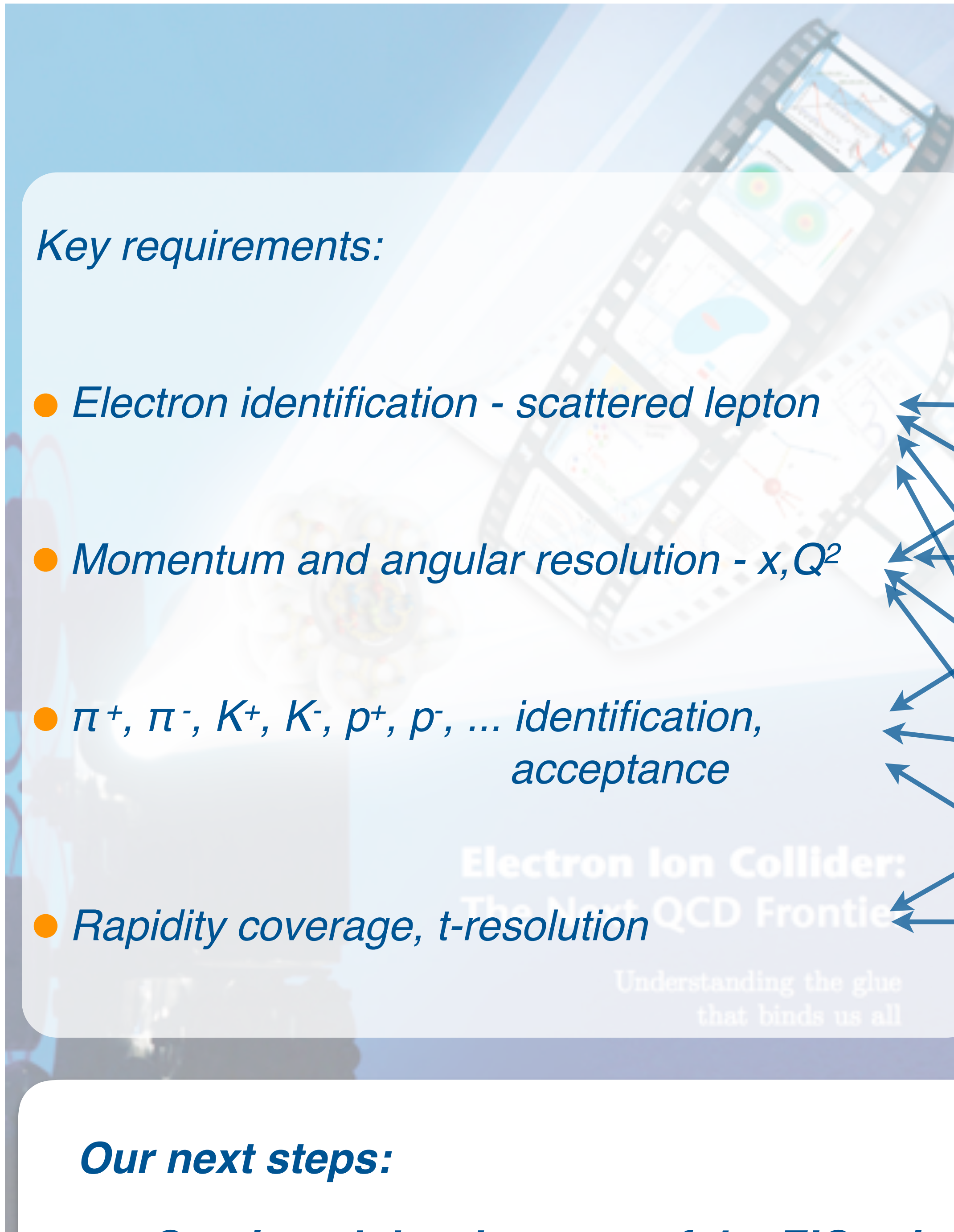
U.S. Based Electron Ion Collider



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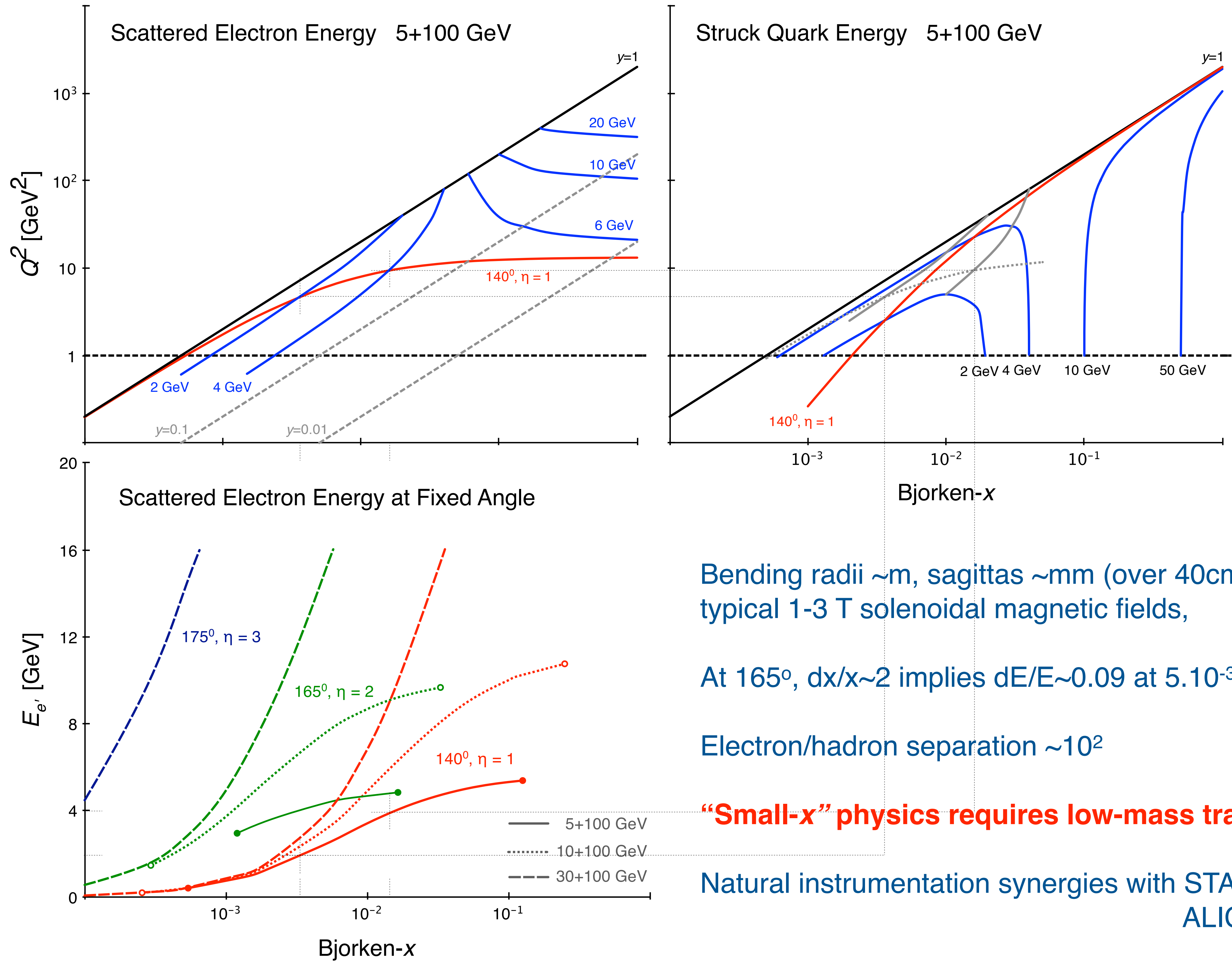
Key measurements:

- *Inclusive Deep-Inelastic Scattering,*
- *Semi-inclusive deep-inelastic scattering with one or two of the particles in the final state,*
- *Exclusive deep-inelastic scattering,*
- *Diffraction.*

Our next steps:

- ***Continued development of the EIC science case***
- ***Towards instrumenting the EIC***

U.S. Based Electron Ion Collider



Bending radii ~m, sagittas ~mm (over 40cm), in typical 1-3 T solenoidal magnetic fields,

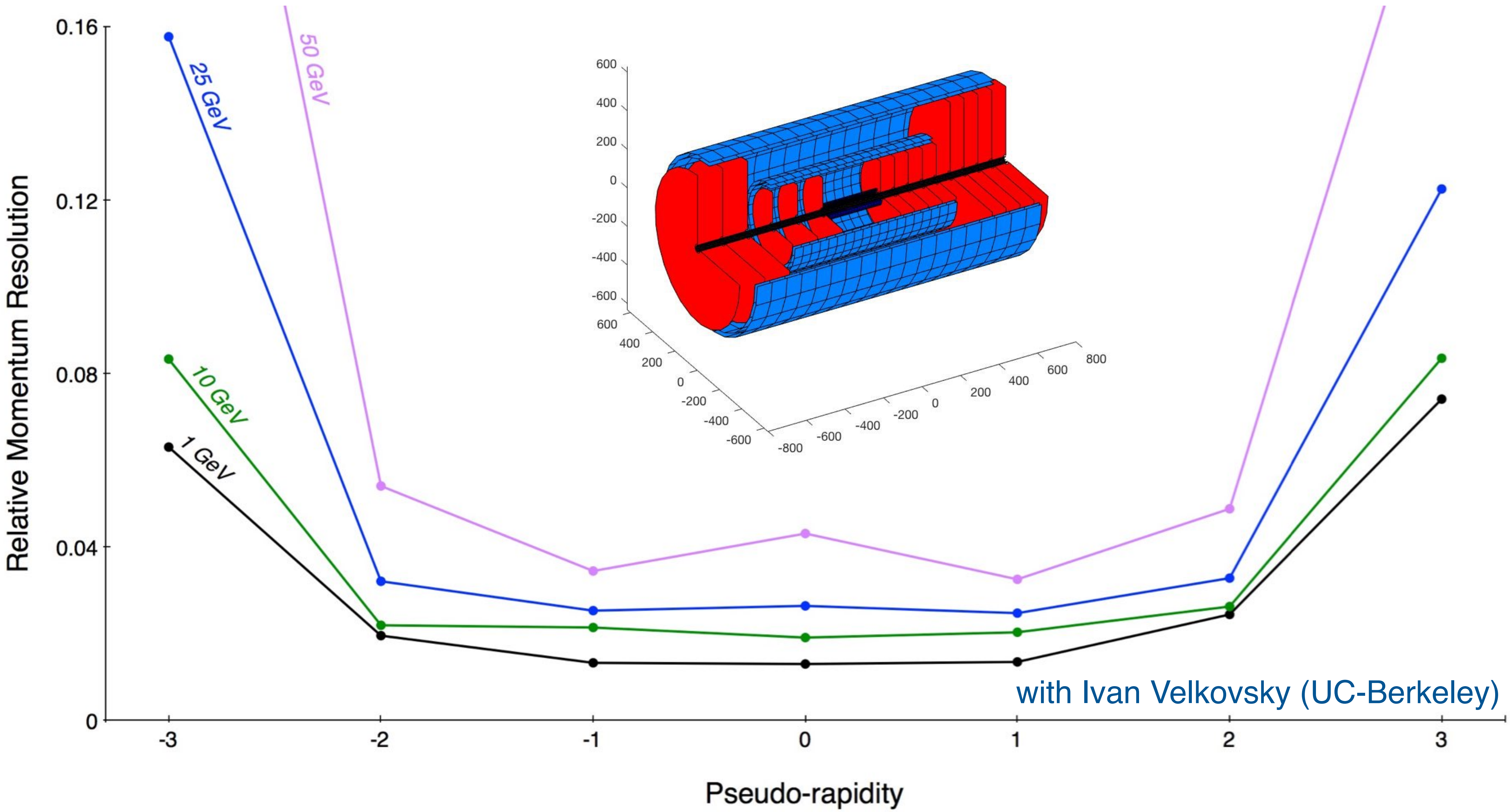
At 165º, dx/x~2 implies dE/E~0.09 at 5.10^{-3}

Electron/hadron separation ~10^2

"Small-*x*" physics requires low-mass tracking,

Natural instrumentation synergies with STAR-HFT ALICE-ITS.

U.S. Based Electron Ion Collider



Note: this is an illustration of ongoing work, not a "proposal",
it shows prel. performance of an ALICE-ITS tracker, complemented with forward Si-disks, in a 1.5 T field,

Synergies with with STAR-HFT, ALICE-ITS, ***and Barbara Jacak's research group at UC-Berkeley,***

Development of forward Si-tracking is supported, in parts, through the BNL generic EIC R&D program, as **eRD16.**

U.S. Based Electron Ion Collider

As of FY17, RNC's EIC ambitions are supported also through the LBNL LDRD:

Spencer Klein et al, "R&D towards an Electron-Ion Collider."

- studies of photonuclear and two-photon physics at an EIC,
- simulations to optimize the dimensions and number of barrel layers of a low-mass inner silicon tracker for the EIC,
- (accelerator physics activities for the two, BNL and JLab, designs)

UC-Berkeley / LBNL hosted the 2016 Electron Ion Collider User Group Meeting,

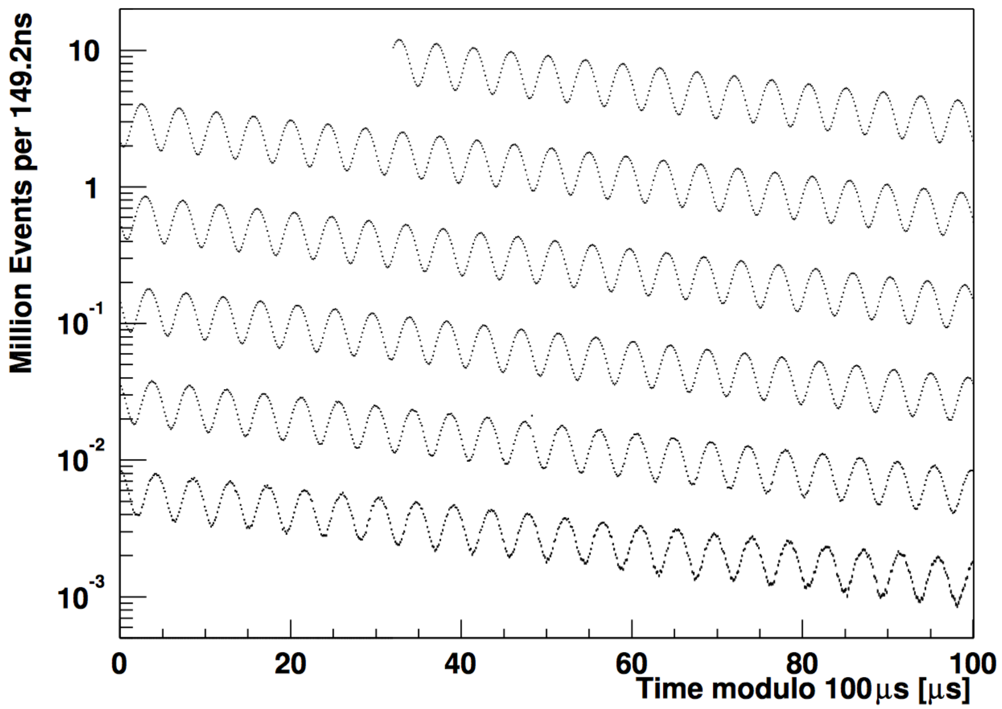
Barbara Jacak has initiated the formation of a California Consortium

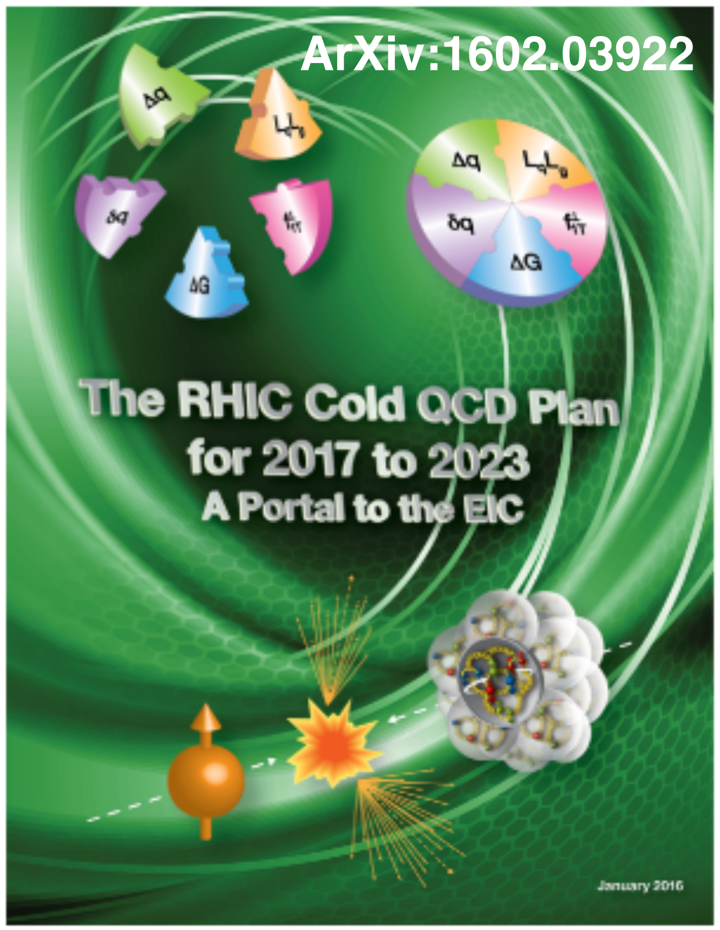
- instrumental also in establishing the "Q2C LDRD" program,
- inaugural meeting past July 20 and 21 at LBNL


MIND THE GAP

Bridging the Gap

- Muon g-2, a textbook spin-physics measurement,
  Phys. Rev. D73 (2006) 072003, 1269 citations
  Unique experience in magnetic field measurement
  Follow-up experiment, E989, at FNAL
  Conditional DOE support to (re-)engage in Jul'13
  NSD management stalled and nixed effort in Apr'14



- 

Requested by DOE Office of Science Nuclear Physics during its Summer 2015 BNL site visit (MENP, "Spin Plan"),

Favorably reviewed by BNL PAC,

Awaiting DOE feedback.

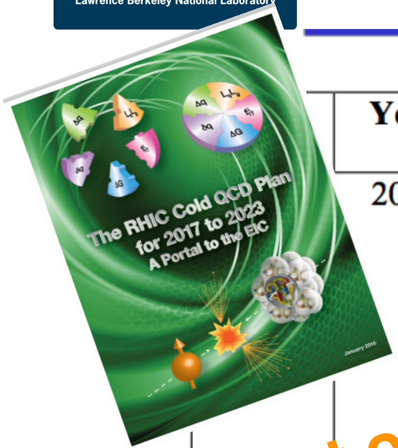
- Well aware that MENP priorities are shifting to the JLab 12GeV program

Bridging the Gap

	Year	$\sqrt{s}$ (GeV)	Delivered Luminosity	Scientific Goals	Observable	Required Upgrade
Scheduled RHIC running	2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3 First look at GPD Eg	A_N for γ, $W^{\pm}$, Z^0, DY $A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets A_{UT} for J/Ψ in UPC	A_N^{DY}: Postshower to FMS@STAR **None** **None**
	2023	$p^{\uparrow}p$ @ 200	300 pb^{-1} 8 weeks	subprocess driving the large A_N at high x_F and η evolution of ETQS fct. properties and nature of the diffractive exchange in p+p collisions.	A_N for charged hadrons and flavor enhanced jets A_N for γ A_N for diffractive events	Yes Forward instrum. **None** **None**
	2023	$p^{\uparrow}Au$ @ 200	1.8 pb^{-1} 8 weeks	What is the nature of the initial state and hadronization in nuclear collisions Nuclear dependence of TMDs and nFF Clear signatures for Saturation	R_{pAu} direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAu}(DY):Yes Forward instrum. **None** Yes Forward instrum.
	2023	$p^{\uparrow}Al$ @ 200	12.6 pb^{-1} 8 weeks	A-dependence of nPDF, A-dependence of TMDs and nFF A-dependence for Saturation	R_{pAl}: direct photons and DY $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, nuclear FF Dihadrons, γ-jet, h-jet, diffraction	R_{pAl}(DY): Yes Forward instrum. **None** Yes Forward instrum.
Potential future running	202X	$p^{\uparrow}p$ @ 510	1.1 fb^{-1} 10 weeks	TMDs at low and high x quantitative comparisons of the validity and the limits of factorization and universality in lepton-proton and proton-proton collisions	A_{UT} for Collins observables, i.e. hadron in jet modulations at $\eta > 1$ and mid-rapidity observables as in 2017 run	Yes Forward instrum. **None**
	202X	$\vec{p}\vec{p}$@ 510	1.1 fb^{-1} 10 weeks	$\Delta g(x)$ at small x	A_{LL} for jets, di-jets, h/γ-jets at $\eta > 1$	Yes Forward instrum.

Table 1-2: Summary of the Cold QCD physics program propsed in the years 2017 and 2023 and if an additional 500 GeV run would become possible.

Bridging the Gap



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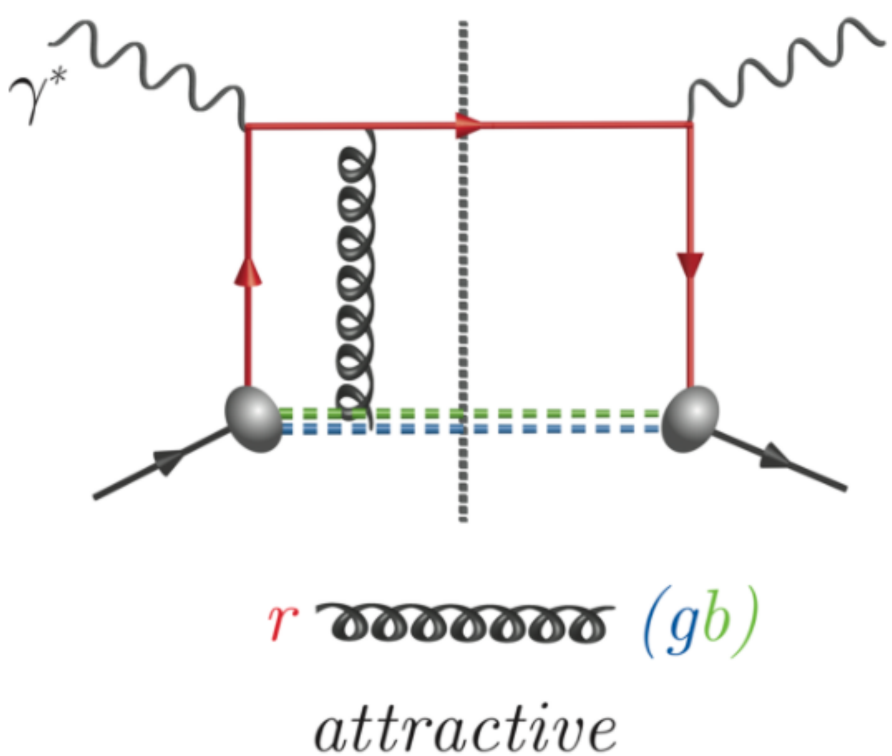
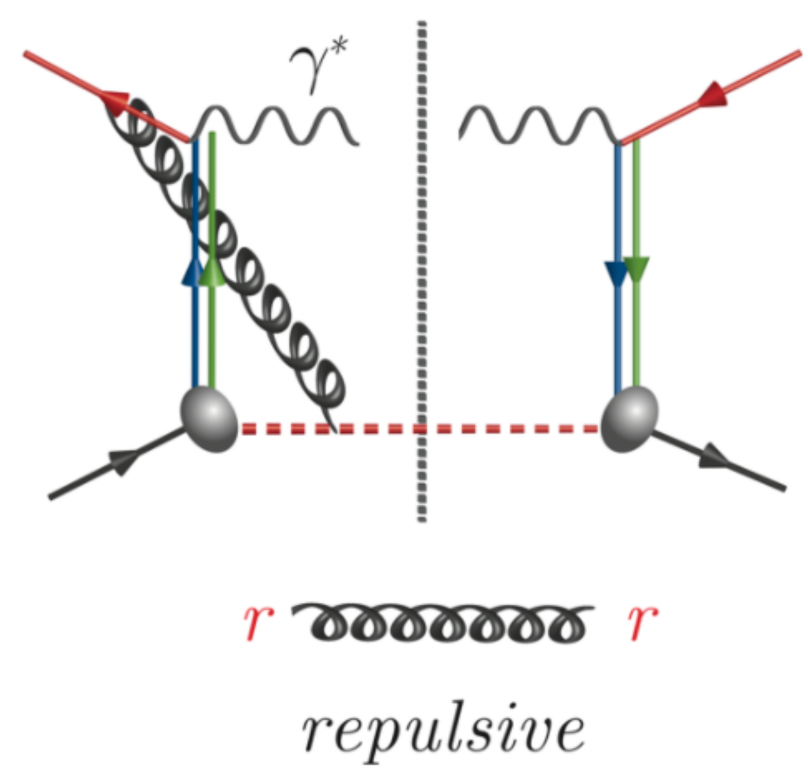
2017	$p^{\uparrow}p$ @ 510	400 pb^{-1} 12 weeks	Sensitive to Sivers effect non-universality through TMDs and Twist-3 $T_{q,F}(x,x)$ Sensitive to sea quark Sivers or ETQS function Evolution in TMD and Twist-3 formalism	A_N for γ, $W^{\pm}$, Z^0, DY	A_N^{DY}: Postshower to FMS@STAR
			Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3	$A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets	**None**
			First look at GPD E_g	A_{UT} for J/Ψ in UPC	**None**

Firmly part of the plan, on track for 2017

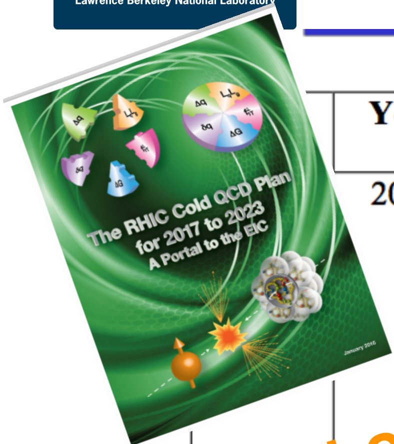
DIS



DY



Bridging the Gap



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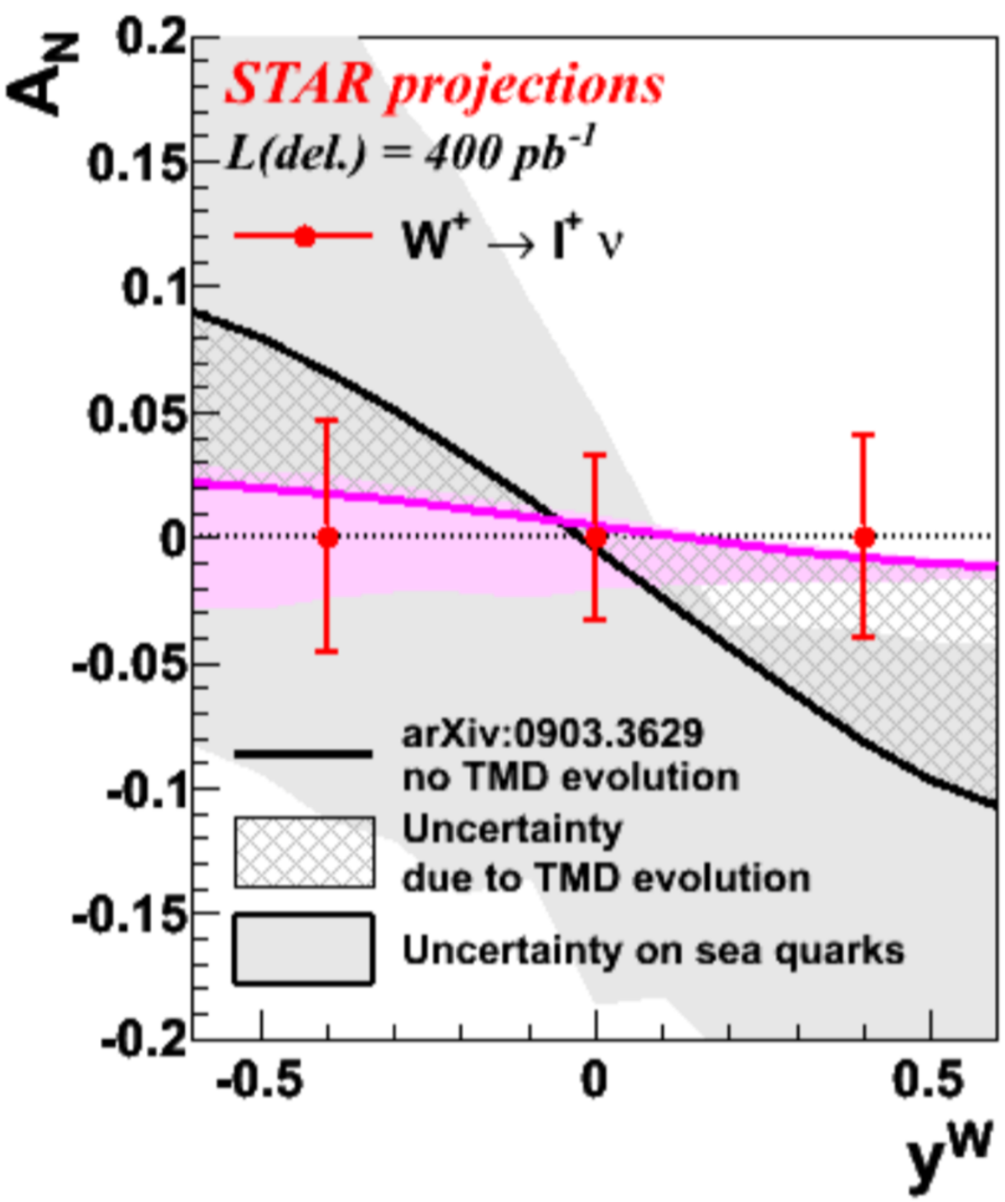
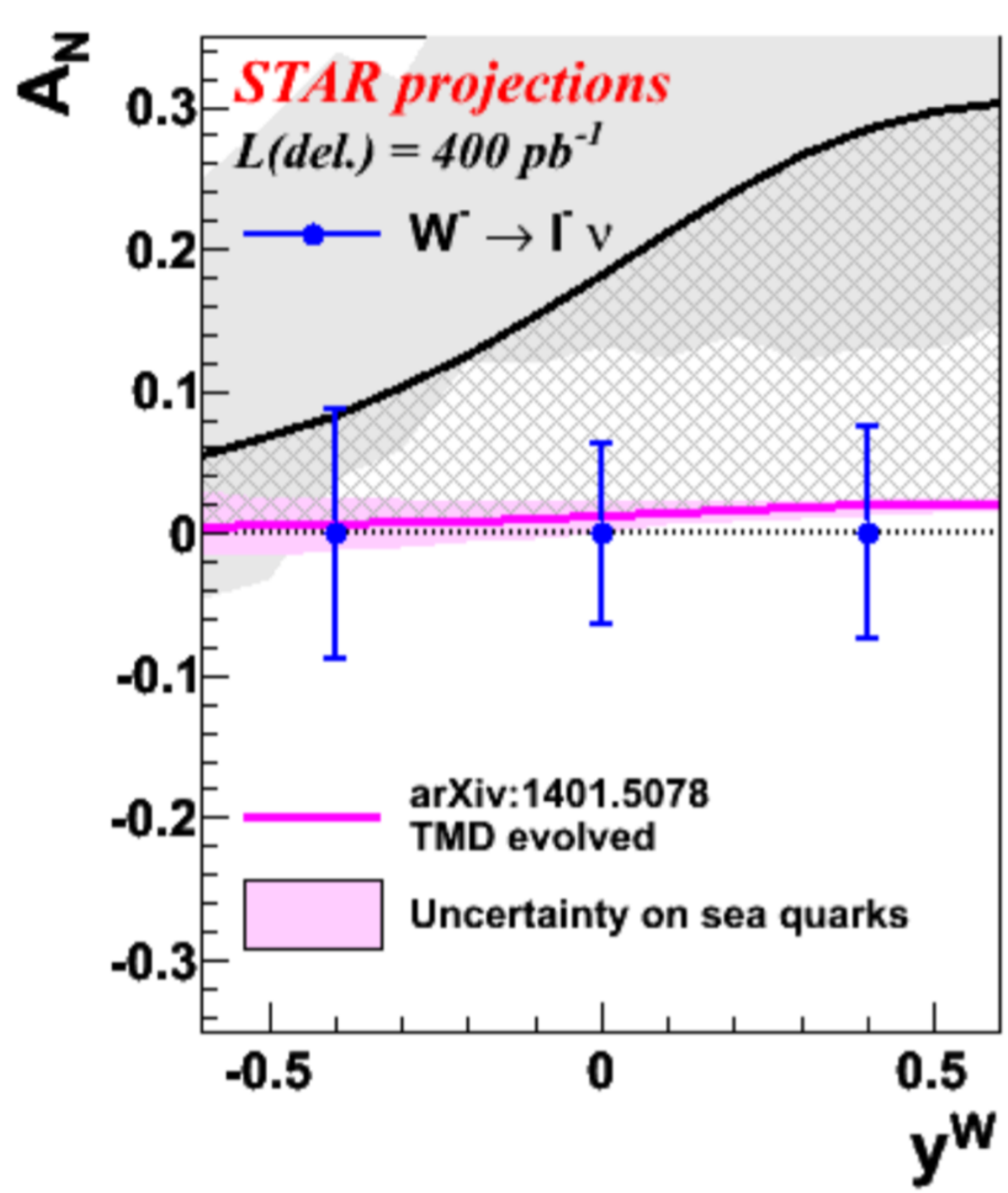
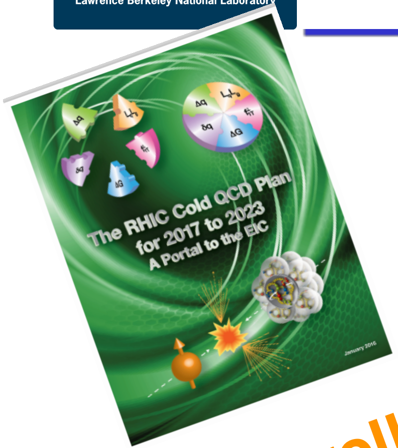
			Transversity, Collins FF, linearly pol. Gluons, Gluon Sivers in Twist-3	$A_{UT}^{\sin(\phi_s-2\phi_h)}$ $A_{UT}^{\sin(\phi_s-\phi_h)}$ modulations of $h^{\pm}$ in jets, $A_{UT}^{\sin(\phi_s)}$ for jets	**None**
			First look at GPD *Eg*	A_{UT} for J/Ψ in UPC	**None**

Firmly part of the plan, on track for 2017

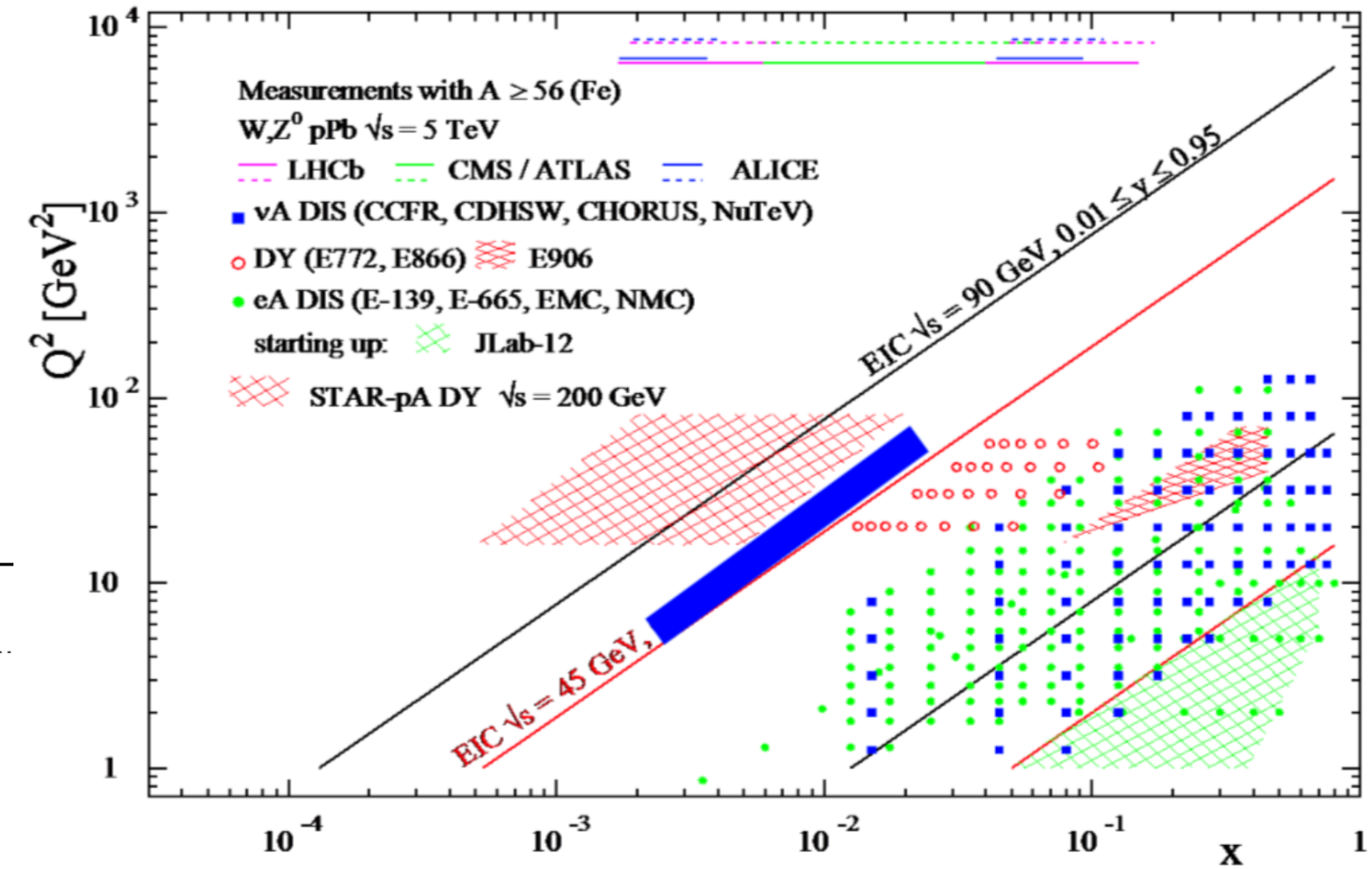


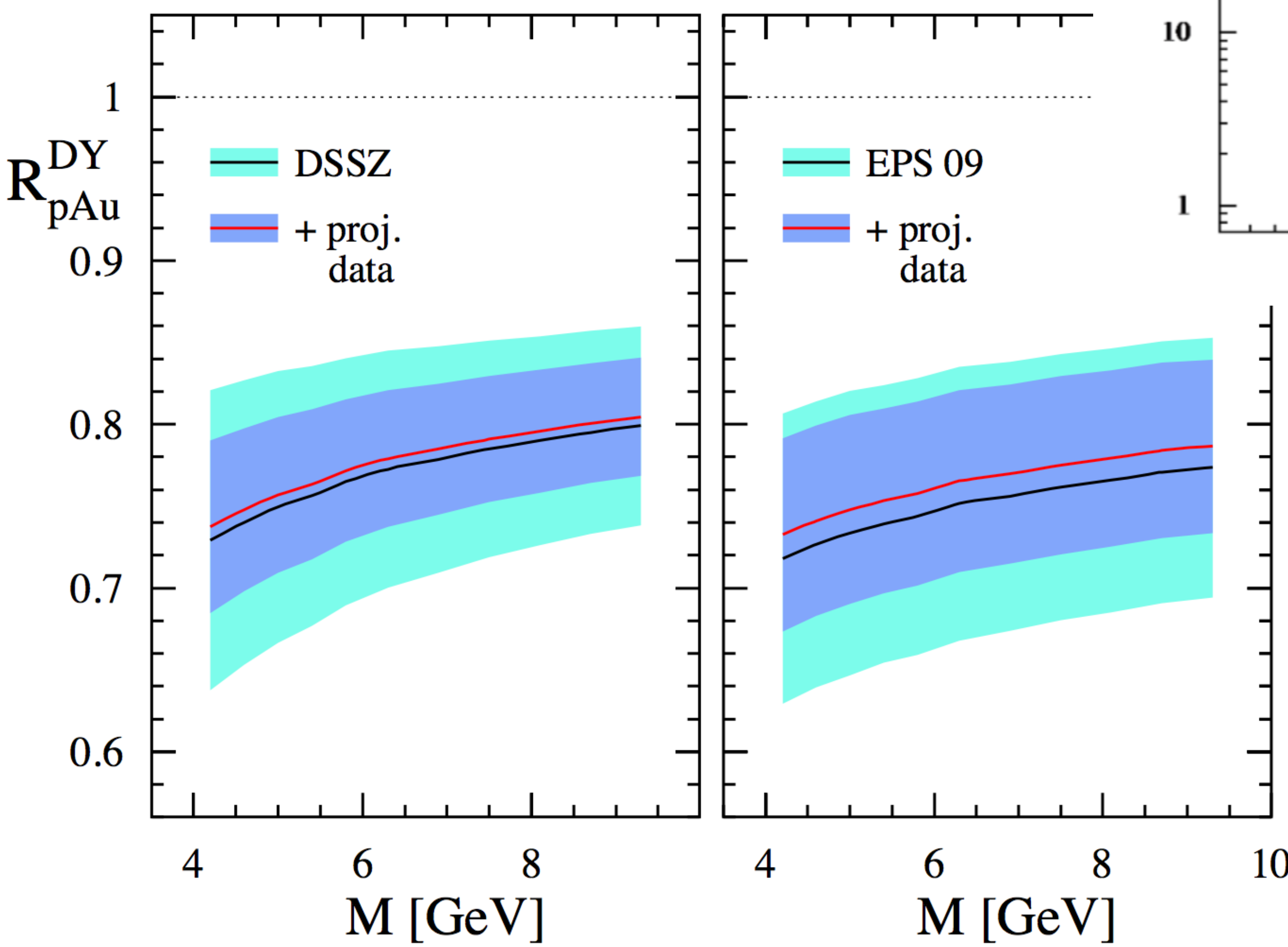


Bridging the Gap



Nuclear Drell-Yan





Unique acceptance at small-*x*, *also* in the EIC era

Requires new forward instrumentation,
- implementation plans exist for both experiments,
- STAR proposal in preparation*

Closing Comments

RHIC spin program:

- has achieved the most sensitive insights in **gluon polarization** in the nucleon,
  gluons are positively polarized for momentum fractions $x > 0.05$,
  at the level of 0.2 h for $Q^2 = 10$ GeV^2
- has provided evidence, with measurements at the W-mass scale that are free of fragmentation uncertainties, of non-perturbative **sea-quark polarization**,
- is *now* on track to acquire transverse W-boson, Drell-Yan, and photon data on the **Sivers' sign-change.**

RHIC cold-QCD plan for 2017-2023 (arXiv:1602.03922):

- outlines, and in many cases quantifies, new opportunities within constraints on beam-use scenarios and upgrades: **nuclear Drell-Yan** is a prime example,
- advocates* timely realization of a modest **forward calorimetry and tracking upgrade**, renewed **$\sqrt{s}$ = 500 GeV beam-operations** for precision measurements of Sivers, Collins, and gluon polarization measurements,
- awaits DOE feedback,

EIC at LBNL:

- is progressing beyond the developing the 2015-LRP EIC science case, Eur. Phys. J. A52 (2016) no.9, 268,
- to include forward Si-tracking under the eRD16 of the generic EIC R&D program,
  FY17 LDRD under the Laboratory's Quantum to Cosmic initiative (science case and instrum.),
  initial formation of an California Consortium.